Compatibility between radiocommunication & ISM systems in the 2.4 GHz frequency band

Final Report

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ABSTRACT

Investigations have been made into the co-existence of a variety of radiocommunication and ISM systems in the 2400 - 2483.5 MHz frequency band, to determine whether the band will be capable of supporting a reasonable quality of service for both public radio fixed access (RFA) services and all the private, unlicensed telecommunication systems which are likely to be deployed in the band. The investigations included statistical modelling of various interference scenarios and market penetration levels.

The report identifies a number of technological issues relating to system co-existence in this frequency band and concludes that:

- There is already a significant amount of RF activity and there is likely to be a substantial increase in the future as increasing numbers of communication devices are deployed in the band.
- Types and levels of interference vary considerably both geographically and over time   Currently, the highest peak levels of interference at most locations are likely to be from ISM equipment and OBTV transmissions. However, as penetration levels increase, outdoor communication systems (RLANs and wireless bridges) are expected to become the most significant sources of interference.
- The effect of increasing levels of interference is likely to be a reduction in the maximum working range of radiocommunication systems in the band.
- Operation of high performance telecommunication networks in a very dense urban environment such as the City of London "square mile", which is also subject to a relatively high number of OBTV transmission, is unlikely to be viable. Operation of a single such network in other more typical urban areas should be viable in most instances, providing due account is taken of the projected future increase in interference levels.

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1 INTRODUCTION

This report describes investigations made into the co-existence of a variety of radiocommunication and industrial, scientific and medical (ISM) systems in the 2400 – 2483.5 MHz (2.4 GHz) frequency band. The investigations were carried out by Aegis Systems Ltd, on behalf of the UK Radiocommunications Agency (RA). The principal objectives were to determine whether there is sufficient radio spectrum capacity within the 2.4 GHz band to support a reasonable quality of service for both public radio fixed access (RFA) services and all the private, unlicensed telecommunication systems which are likely to be deployed in the band.

The study takes into account all the currently known operational systems and sources of interference in the 2.4 GHz band, including those that are planned for deployment in the foreseeable future. These include:

- RFA (both POTS and data)
- Radio Local Area Networks (RLANs) and other wireless connectivity systems
- Outside Broadcast Television (OBTV)
- ISM equipment
- Sulphur Plasma Lighting
- Short Range devices (SRDs), including RF tags, audio and video links.

The report provides detailed technical information relating to the systems and technologies used in the 2.4 GHz band and presents analyses of the interference likely to arise between various combinations of interferer and victim. Worst case interference between specific systems has been analysed on a minimum coupling loss basis and statistical analysis has been carried out for scenarios where a large number of interferers are involved.

The investigations have shown that:

- there is already a significant amount of RF activity in the 2.4 GHz band and there is likely to be a substantial increase in the future as increasing numbers of communication devices are deployed in the band.
- The types and levels of interference vary considerably both geographically and over time Currently, the highest peak levels of interference likely to be encountered at most locations originate from ISM equipmentand OBTV transmissions. However as penetration levels increase outdoor communication systems, notably RLANs and wireless bridges, are expected to become the most significant interference factor
- Outdoor communication systems will tend to be self limiting in that their own performance and coverage range will suffer at higher penetration levels.
- The practical effect of interference on those installing public or private networks designed to meet specific performance criteria will be to reduce the working range over which those criteria can be met

- operation of high performance telecommunication networks in the City of London "square mile", which in addition to having an exceptionally high density of potential RLAN users is also subject to a relatively high number of OBTV transmissions, is unlikely to be viable. Operation in other, more typical urban areas should be feasible providing sufficient flexibility exists to increase link margins to counter projected future interference levels.
- interference between co-located high capacity networks is likely to rule out the possibility of two uncoordinated high capacity networks in the same geographic area maintaining a grade of service consistent with the requirements of a public telecommunications operator.
- on the basis of currently available technology and recent standards developments, it is likely that FHSS systems will provide greater resilience to interference and will therefore be preferable for applications such as RFA where it is necessary to deliver a specific grade of service.

In the light of these results it is recommended that those planning networks at 2.4 GHz should take account of the likely increase in interference levels as system penetrations rise, and build sufficient flexibility into their networks to deliver the increased link margins which may become necessary as a result.

It is unclear at this stage how diverse a range of applications may arise for the emerging HomeRF and Bluetooth technologies. This study has assumed a high penetration of these technologies and allowed for a substantial element of outdoor use, which should provide something approaching a realistic worst case scenario. However, it is recommended that a further evaluation of the various interference scenarios in the band be carried out when the direction of market development for these technologies has become more clear.

2 RADIO TECHNOLOGIES IN THE 2.4 GHZ BAND

This section of the report considers each of the radio technologies either currently used in the band or planned for future deployment, with a particular emphasis on their potential as interferers into public or private 2.4 GHz telecommunication systems. The largely unregulated nature of the 2.4 GHz band means that many different RF technologies may be legitimately deployed in the band. Telecommunication systems such as RFA or RLANs must therefore be specifically designed to withstand unpredictable and potentially severe levels of interference. This is achieved by using spread spectrum technology, a technique originally developed by the military to resist interception and jamming of radio transmissions by the enemy. A fuller description of the receiver parameters and the techniques used to minimise the effects of interference to these systems can be found in section 3.

Conventional analogue and digital RF technologies are also widely deployed in the 2.4 GHz band, principally for OBTV applications and a variety of SRDs. The largest use of the band globally is still ISM equipment, although there is increasing interest in industrial RF heating and lighting applications.

2.1 Spread Spectrum

Spread Spectrum is the principal enabling technology for communication applications in the 2.4 GHz band, providing resilience against the many other potential interference sources in the band. It has its origins in spread spectrum communication systems developed by the military as early as the 1940s, the objective being to reduce the likelihood of radio signals being either intercepted or jammed by the enemy.

Conceptually the technique is relatively straightforward, involving the multiplication of the wanted information signal by another, wide band, signal called a *spreading code*. In principle, this code could take any form – wide band noise or frequency modulation for example – but over the years two specific coding techniques were found to be most effective. These have become known as:

- **Frequency Hopping Spread Spectrum (FHSS),** where the coding signal is a pseudo random sequence of discrete sinusoidal carriers, each at a different radio frequency
- **Direct Sequence Spread Spectrum (DSSS),** where the coding signal comprises a pseudo random sequence of positive and negative pulses at a very high repetition rate

The coded signal typically has a bandwidth many times that of the original information signal (the actual ratio is referred to as the *coding gain* and provides an indication of the resilience of the signal to other co-channel interference). Decoding of the transmitted signal is achieved by applying a replica of the spreading code at the receiver. This process provides a further benefit, in that the replica code has the effect of spreading any unwanted interference signals by a factor equivalent to the coding gain. By applying a narrow band filter after the decoder, most of the interference can be rejected, leaving a relatively unimpaired information signal.

The presence of a second spread spectrum signal with a different code has a similar effect, i.e. the unwanted signal will remain in its coded wide band form and will be ignored by the receiver. The ability to code signals with a large number of different (orthogonal) codes leads to the concept of *Code Division Multiple Access (CDMA)*, which can be used as an alternative to established frequency and time division multiple access (FDMA and TDMA) technologies. A particular attraction of CDMA is that conventional frequency planning and co-ordination is not required, since it is the coding rather than the carrier frequency that differentiates between different users or cells. Thus it is possible in principle to operate an entire wide area fixed or mobile network on a single wideband radio channel.

The principal disadvantages of spread spectrum transmission are a relatively high digital signal processing (DSP) overhead and, particularly for DSSS, a requirement for the received signals from all users to be nominally equal. The latter is required to prevent nearby subscribers overpowering the base station receiver and drowning out the signals from far away subscribers, the so-called "near-far" effect. However, DSP technology development and cost reduction have reached the stage where these requirements are more than justified by the benefits of simpler network planning and greater interference resilience.

FHSS is currently the predominant technology for telecommunication systems at 2.4 GHz. However there is increasing interest in DSSS systems as these are able to deliver significantly greater bit rates. The development in the early 1990s of an ETSI[1] standard (ETS 300 328) for spread spectrum data transmission in the 2.4 GHz band and an IEEE[2] interoperability standard (802.11) for spread spectrum RLANs has accelerated the development of both FHSS and DSSS equipment, which is now seen as an increasingly attractive and flexible complement to conventional wired infrastructures.

2.1.1 Frequency Hopping Spread Spectrum (FHSS)

In FHSS, the spreading code is used to control a frequency agile local oscillator, the output of which is used to upconvert the modulated IF carrier to the 2.4 GHz band. The resulting RF output is referred to as a *hopping sequence*. A replica of the spreading code is applied at the receiver to recover the wanted information signal. Other FHSS transmissions with different hopping sequences are rejected by the narrow band IF filter, along with any wide band signal or noise content.

The European standard, ETS 300 328, requires FHSS systems to hop between at least 20 non-overlapping radio channels within the 2.4 GHz band, with a dwell time on each channel of not more than 400 msec. Each radio channel must be occupied at least once within a period equal to the product of the channel dwell time and the number of channels, implying a uniform probability of transmission. The maximum bandwidth of a single hopping channel is 1 MHz. CEPT[3] ERC Recommendation 70-03[4] defines the following EIRP[5] limits for ETS 300 328 compliant FHSS systems:

[1] European Telecommunications Standards Institute

[2] Institute of Electrical and Electronic Engineers

[3] Conference of European Post and Telecommunications Administrations

[4] "Wide band data transmission systems using spread spectrum technology in the 2.5 GHz band", 1992

[5] Effective Isotropically Radiated Power

- Total EIRP: -10 dBW
- Peak EIRP: -10 dBW / 100 kHz

FHSS is a form of CDMA, whereby a large number of transmissions can occupy a given frequency band by deployment of different spreading codes. The coding gain of an FHSS system is effectively the number of hopping channels divided by the individual channel bandwidth, i.e. 78 (= 18.9 dB) for a typical 78 channel system.

2.1.2 Direct Sequence Spread Spectrum (DSSS)

DSSS is increasingly being considered for higher bandwidth RLAN applications and may in the future be put forward as an option to deliver broadband RFA services. The process involves multiplying the baseband data signal by a wider bandwidth signal, which takes the form of a pseudorandom binary code.

ETS 300 328 defines all spread spectrum modulation schemes which do not conform to the above requirements for FHSS as DSSS. No limits are defined for the bandwidth of the spread spectrum signal, so long as the transmitted power envelope lies within the 2400 – 2483.5 MHz band. CEPT ERC Recommendation 70-03 limits the peak EIRP spectral density to – 20 dBW / MHz. The maximum RF bandwidth currently used by commercially available 2.4 GHz DSSS systems is c. 30 MHz and the coding gain is typically 10 - 11 dB. Note that this coding gain is not sufficient to deliver effective CDMA, hence co-located DSSS systems generally must operate on different carrier frequencies.

2.2 OBTV

2.2.1 Analogue Systems

Analogue broadcast links are deployed currently on fixed carrier frequencies at 20 MHz intervals within the 2.4 GHz band (i.e. 2400 to 2480 MHz inclusive). According to JFMG Frequency Management, who license these links on behalf of the RA, systems can be deployed substantially anywhere in the UK, except for certain defined exclusion zones which we understand from the RA are to prevent interference with military services. The maximum EIRP for terrestrial OBTV systems is 40 dBW. Airborne links can also be deployed, at altitudes up to 500 feet and with up to 23 dBW EIRP, depending upon the channel used.

Links used by broadcasters at these frequencies fall broadly into three categories:

- Temporary point-to-point links
- Short-range links, from a mobile camera to a fixed point
- Air-to-ground / ground-to-air links

The first of these applications might be represented by a link established from a parabolic antenna mounted on the roof of a vehicle at a racecourse to a similar antenna on a ‘midpoint’ vehicle on a hilltop some 10-20 km distant. The midpoint vehicle might then relay the signal to a permanent OB receiver site at a studio centre or transmitter. The link would be characterised by highly directive antennas at both ends and a line-of sight path. Such point-to-point links can also be established at short notice for electronic news gathering purposes and, in this application, paths are often diffracted, with little or no fading margin.

While demand for terrestrial point to point OBTV links of this type is declining, as alternatives such as cable and satellite become more widely available, continued deployment is likely in scenarios where such alternatives are not feasible. One example is in city centres where the presence of tall buildings may hinder satellite visibility and where the demand justifies the fixed infrastructure required. Such locations are of course also where demand for RLANs and other 2.4 GHz radiocommunication services are likely to be greatest.

The second application would, typically, be that of a handheld camera at a sporting event, relaying pictures over a few hundred metres to a fixed receive point. The camera antenna will normally be omnidirectional, and may operate to a directional receive antenna which is manually tracked. Transmitted power levels in this scenario are typically 5 watts EIRP.

The airborne link case might be represented either by a helicopter-mounted camera following a motor racing event and relaying the pictures to a ground receiver, or by a camera mounted in a racing car, transmitting to a helicopter ‘midpoint’, which then re-transmits the pictures. The mobile nature of both of these applications means there is unlikely to be any practical substitute for radio links in the foreseeable future.

For the purposes of interference modelling, the following systems will be investigated:

(i) Handheld camera, (7 dBW EIRP)

(ii) High power temporary point to point link (40 dBW EIRP)

In both cases an analogue FM transmitter is assumed, with a 20 MHz bandwidth, and a spectral mask conforming to that given in Appendix 4 of CEPT ERC Report 38, reproduced in the next figure.

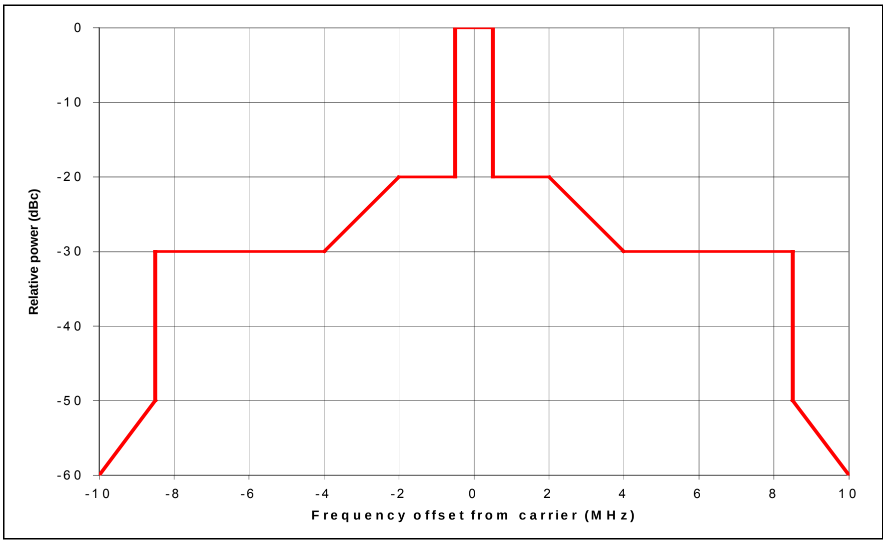


Figure 2.1 Representative spectrum mask for analogue OBTV video links.

It can be seen that the power at greater than +/- 0.5 MHz from the channel centre is at least -20 dB with respect to the carrier. The two representative system types assumed in the report are illustrated in Figure 2.2 below.

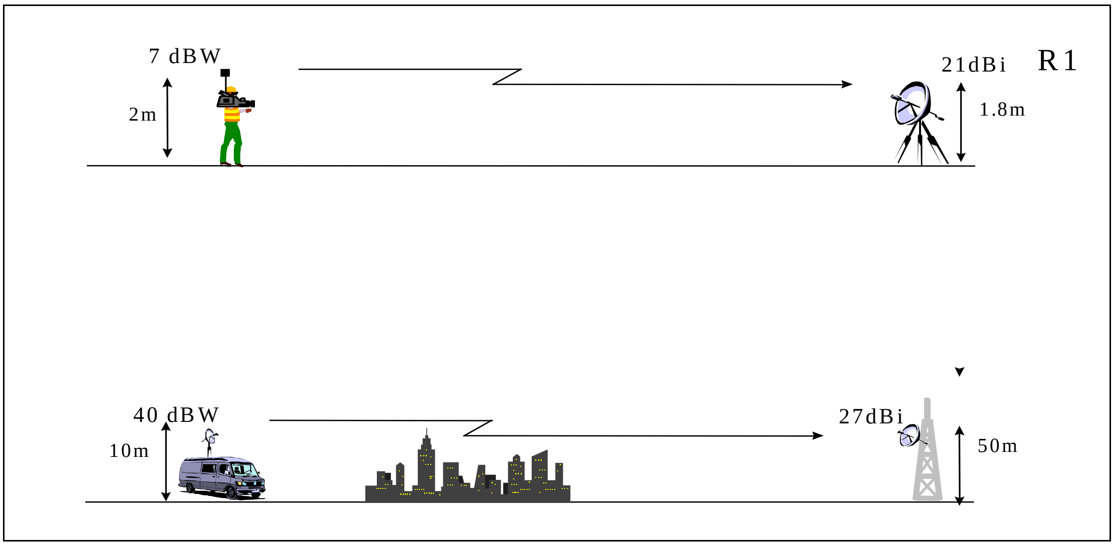


Figure 2.2 Types of OBTV system at 2.4GHz

The increasing proliferation of broadcast television services, many with an emphasis on sports and news coverage, is likely to lead to greater use of mobile OBTV services over time. Much of this increased demand will focus on the 2.4 GHz band as other parts of the spectrum face restrictions to protect other services such as mobile satellites.

2.2.2 Digital Systems

One way that the increasing demand for OBTV in the 2.4 GHz band may be accommodated in the longer term is by the introduction of digital technology. Since the main growth areas are likely to be mobile applications, a multipath resistant modulation scheme such as OFDM[6] is likely to be favoured. This is capable of conveying 8 Mbit/s (the minimum bit rate for broadcast quality video using current compression technology) in an RF bandwidth of 7 MHz, with the following typical spectrum mask:

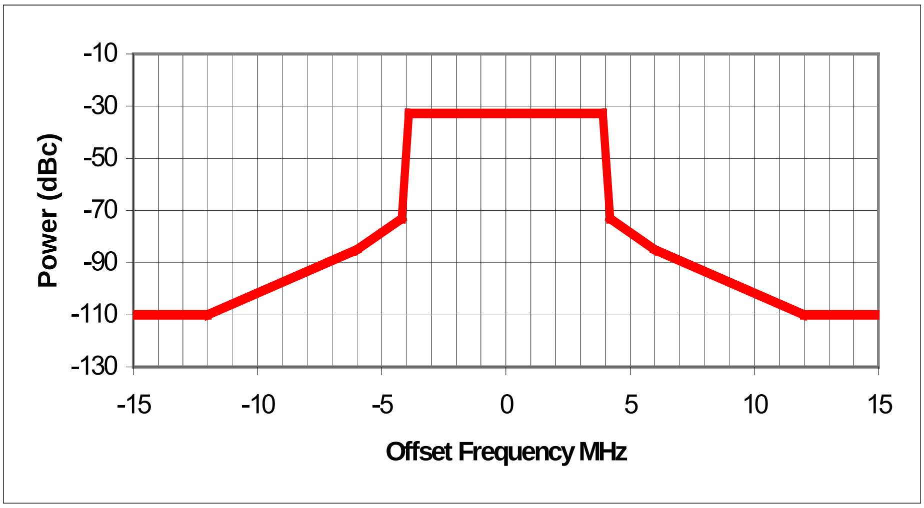


Figure 2.3 Transmitter Spectrum mask for OFDM digital OBTV link

[6] Orthogonal Frequency Division Multiplex

According to the RA's Broadcasting Policy Management Unit, use of the 2.4 GHz band for OBTV transmissions is largely short term and sporadic. In 1998-99 there were 485 assignments in the band, lasting on average 1-2 days, spread over about 200 locations throughout the UK.

There are, however, some locations where frequencies are regularly used. They are mainly race courses (Cheltenham, Doncaster, Kempton Park, Sandown Park, Newmarket and Haydock Park) and motor racing circuits (Silverstone, Brands Hatch, Donnington Park and Thruxton). There has also been frequent use in a Glasgow night club. There are also many uses throughout the year within Greater London, principally for relaying signals to permanent receiver sites such as Crystal Palace .

There are specific channels used for news gathering that may be used without notice: 2400 MHz may be used anywhere within the UK and 2480 MHz within the Tyne Tees region. 2460 MHz and 2480 MHz are used for a similar purpose locally in Cardiff and Taunton respectively.

2.3 Industrial Scientific and Medical (ISM) Systems

Article S15.13 § 9 of the Radio Regulations requires administrations to “take all practicable and necessary steps to ensure that radiation from equipment used for industrial, scientific and medical applications is minimal” within the bands designated for such use. To comply with the EU Directive on Electromagnetic Compatibility (89/336/EEC), ISM equipment must also comply with the emission limits defined in standard EN 55011[1]. These are currently under review at frequencies above 1 GHz. Suppliers claim that all equipment meets the internationally recognised limit for exposure to non-ionising radiation of 5 mW/cm^2.

2.3.1 Domestic Microwave Ovens

Domestic Microwave ovens employ cavity magnetrons, which generate RF radiation at a nominal frequency of 2450 MHz and a CW power level of typically 600 – 1200 watts. In operation, the magnetrons are operated either continuously for the duration of the cooking cycle, or pulsed on and off over a period of several seconds in the case of lower power operation (e.g. for defrosting frozen food).

Investigations carried out by the RA[7] show a variation in the frequency and level of emissions from microwave ovens, depending upon factors such as the age of the unit and the heating load, but in general a 30 dB bandwidth of c. 200 MHz, nominally centred on 2.44 GHz, was observed. The 3 dB power bandwidth for an individual microwave oven is typically 1 MHz.

Figure 2.4 shows the envelope of emissions from a sample of 16 different ovens tested by the RA laboratory and compares this with the cumulative emissions measured at an elevated site 1 km from the centre of Skipton in Yorkshire (a typical medium sized town)[8]. Note the asymmetry of the laboratory emissions, with the presence of significantly greater power in the lower sideband. Actual RF power leaking from the ovens tested varied from 1.55 W to 245

[7] Radio Technology and Compatibility Group report no. RTL458, "Investigation to characterise domestic microwave ovens for RA3/PN", March 1998

[8] RA monitoring report no. ML 9721, “Microwave signal activity in the 2.4 GHz band in Ilkley and Skipton”, August 1997

mW (31.9 – 23.9 dBm). Assuming a rated RF power output of 750 W, this represents a minimum attenuation of c. 27 dB. The emissions recorded in Skipton cover a noticeably wider band, possibly reflecting the effect of a number of older or malfunctioning ovens. There is also a significant variation according to the time of day, with peaks corresponding to typical meal times when the greatest number of ovens are likely to be operating. The maximum cumulative power density recorded at Skipton in a 1 MHz bandwidth at the receiving antenna input is of the order of –95 dBW. Similar peak levels were recorded during recent monitoring at Welwyn Garden City and in earlier trials in Glasgow. This is therefore assumed to be a realistic peak level for ISM emissions in a built up area.

Microwave ovens are almost exclusively used indoors and it is there that they are likely to have the most significant effect as an interferer. Locating an RLAN receiver adjacent to an oven is almost certain to result in performance degradation, a factor acknowledged by several manufacturers in their installation and operational manuals. It is generally recommended that RLAN terminals should not be located within 2 –3 metres of a microwave oven.

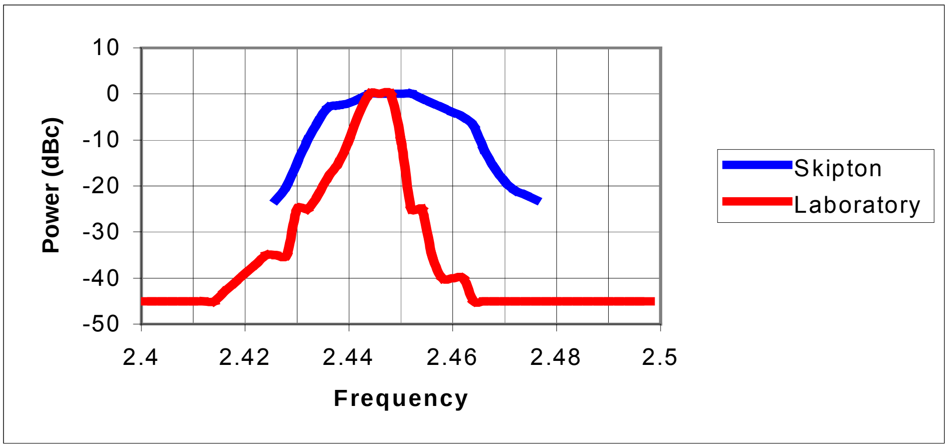


Figure 2.4 Transmit power envelopes for a selection of 16 microwave ovens tested in the RA laboratory, and for ISM radiation in Skipton, Yorkshire

2.3.2 Industrial RF Heating

A number of companies manufacture high power heating systems for use in such applications as food processing, waste sanitation or commercial drying. The powers involved can be up to 50 kW, but equipment is heavily screened to provide operator protection. There is sparse data about the level of emissions from such equipment, but it is assumed that the level of RF screening is comparable to that of domestic ovens, i.e. at least 27 dB. This equates to a power emission of +20 dBW for equipment operating at 50 kW. It is also assumed that the transmission mask is similar to that for domestic microwave ovens (similar magnetrons are involved) and that in practice ISM interference levels in typical urban scenarios are dominated by domestic microwave ovens.

2.3.3 Sulphur Plasma Lighting

This is a relatively recent development in which microwave energy is focussed onto a small quartz sphere that is filled with gaseous sulphur and argon. The energised sulphur provides a highly efficient source of light, which has the further advantage of being close in spectrum terms to natural daylight. The microwave source is a 2.45 GHz magnetron, but power levels can be significantly higher than conventional microwave oven magnetrons. For example, an experimental prototype operating in Washington DC requires an input power of 12 kW. The developer of the technology, Fusion Lighting of the USA, claim it has numerous advantages and are working on a range of indoor and outdoor applications for commercial and industrial use.

Tests carried out by the RA laboratory on a 1.4 kW lamp revealed a worst case EIRP of 394 mW (26 dBm), in the direction of the light beam. The half power bandwidth is c. 6 MHz, indicating a worst case EIRP of 22 dBm / MHz. This is lower than the measured emissions from domestic ovens (3.5.1), despite the higher internal RF power rating but outdoor deployment of higher powered lamps may present a more significant interference risk. It was noted during the tests that emissions fell away considerably away from the main axis of the light beam, although the extent of this has not been quantified.

2.4 Short Range Devices

A diverse range of SRDs can be deployed in the 2.4 GHz band. In Europe, these should conform to CEPT ERC Recommendation 70-03 and the corresponding ETSI standard I-ETS 300 440. These documents define power limits of 500 mW for transponder systems and 10 mW for other types of low power device.

2.4.1 RF Identification (RFID) Systems

The unique code correlation properties of spread spectrum technology makes it suitable for use in RFID systems. Applications for these include automatic vehicle toll collection, inventory and security systems. RFID involves transmission of an encoded interrogation signal, which is processed and returned by a passive transponder “tag” on the item being interrogated. Because of the passive nature of the tag, RFID systems require higher transmit powers than other SRDs.

There are current proposals in CEPT to increase permitted power levels for RFID devices to 5 W[9], however this will be subject to the adoption of various measures to reduce the impact of these higher power devices. These measures include:

- use of downtilted antennas to restrict horizontal EIRP to 500 mW
- restricting operation to specific portions of the band
- applying a maximum duty cycle of 10% or less

Penetration levels of RFID devices are likely to be similar to those of RLAN terminals, however many devices, particularly hand held devices which make up a large proportion of the total, will be used only intermittently. Devices may be deployed in indoor or outdoor locations, however unlike RLANs outdoor systems are intended for short range coverage using low elevation, downtilted antennas. The interference contribution of outdoor RFID

[9] CEPT/ERC document SE24S(98)41, rev 6, "Draft preliminary report for RFID systems operating in the 2.45 GHz ISM band", April 1999

devices is therefore likely to be insignificant relative to outdoor RLAN or wireless bridge installations with highly elevated and in many cases omnidirectional antennas. The interference contribution from indoor RFID devices is likely to be somewhat less than RLANs due to the adoption of the above interference mitigation measures. However, since the operational parameters of RFID devices have yet to be fully agreed, we have assumed that their interference contribution will the same as that for indoor RLAN devices

2.4.2 Audio and Video Links

A number of companies are promoting low power video and audio links for operation within the band. These typically use analogue FM and EIRP levels below 10 mW to be compliant with European and UK regulations for low power devices. Although primarily intended for indoor use they may on occasion be deployed out of doors, e.g. for surveillance closed circuit TV links. Widespread outdoor deployment is considered unlikely due the relatively high susceptibility of analogue fixed frequency devices to interference from other sources in the band. In view of this and the relatively narrow bandwidths and low powers involved, analogue links of this type have not been included in the interference analysis.

2.4.3 Military Systems

It is assumed geographic restrictions on RFA systems will reflect those imposed on OBTV links and that these will also be sufficient to avoid interference from the military into RFA systems. Interference from military systems has not therefore been considered within this study.

3 TELECOMMUNICATION SYSTEMS IN THE 2.4 GHZ BAND

This section provides a detailed overview of the functional and operational characteristics of the various public and private *telecommunication* systems that are the subject of this study. These are RFA, RLANs and other wireless connectivity systems, notably the recently announced *Bluetooth* and *HomeRF* initiatives.

3.1 RFA

3.1.1 Introduction

The term RFA refers to the provision by radio means of the access part of a fixed public switched telecommunications network. An RFA service must match substantially the capability of a conventional, wired PSTN access network. Currently for most users this means that the service must provide, as a minimum, toll quality voice (i.e. of an audio quality comparable to that obtained over a fixed wire network), group 3 fax and data transmission at a minimum rate of 9.6 kbit/s. These basic service capabilities reflect the historical capabilities of analogue wire line services, commonly referred to as *plain old telephony service (POTS)*. However, the introduction of digital services such as ISDN and the availability of improved analogue modems offering data rates of 50 kbit/s or more over conventional analogue lines means that customer expectations increasingly exceed this basic service level.

3.1.2 Narrowband (POTS) RFA services

There is currently one licensed 2.4 GHz RFA service in the UK, operated by Atlantic Telecom in Scotland. Like most current RFA services around the world, this provides a digital radio link between the network and subscriber, using 32 kbit/s adaptive differential pulse code modulation (ADPCM) to digitise the analogue voice signals. A single 32 kbit/s link provides toll quality voice communication and fax but limits the performance of standard V.34 or V.90 modems to typically 9.6 kbit/s (this is because the modem output is a narrow band analogue signal which at higher data rates has complex phase modulation characteristics which cannot be faithfully encoded at 32 kbit/s). A second 32 kbit/s ADPCM link is required to provide performance comparable to the 33 - 56 kbit/s that standard modems can deliver over a conventional analogue line. This in itself is not a problem, as the basic Atlantic technology is capable of delivering an aggregate bit rate of up to 144 kbit/s, however it does have implications for the capacity of the available spectrum. The RFA link uses time division duplex (TDD) and frequency hopping code division multiple access (FH-CDMA) and sends a constant stream of data back and forth when a call is in progress.

The network architecture is broadly similar to that of a cellular mobile telephony network, but without the need for local base station controllers to control small groups of base stations, Instead, each base station is linked directly back to a central switch, via microwave or fibre links. Unlike a conventional wire line service, the subscriber does not have a dedicated connection to the local exchange or concentrator. In RFA networks, the radio base station itself acts as a local concentrator and is designed to provide sufficient lines to cater for anticipated busy hour traffic levels. In Atlantic's case the network is currently planned to cater for busy hour traffic of 100 millierlangs per business subscriber and 70 millierlangs per residential subscriber, with a 1% blocking probability in each case. Interference into the base station receiver may result in the simultaneous loss of service to all subscribers connected to that sector

Each RF transceiver can carry eight POTS channels and up to three transceivers can be accommodated in a single base station sector. The network can thus provide up to 24 POTS channels per sector. For a 1% blocking probability this corresponds to 15.3 erlangs per sector, which in turn allows up to 218 residential or 153 business subscribers per sector at the above erlang and blocking levels.

On this basis it is possible to estimate the numbers of base station sectors which would be required for various levels of penetration, assuming a perfectly uniform geographic distribution of subscribers. For example, assuming

- a 70% penetration level for fixed telephones in the UK
- a 4% share of the total market for the RFA operator[10]
- a population of 744,000 within the operator's service area[11]
- a split of 80 / 20 between residential and business subscribers,

the minimum number of base station sectors required, assuming perfectly uniform population distribution and traffic loading, would be:

(744,000 x 0.7 x 0.04 x 0.8) / 218 + (744,000 x 0.7 x 0.04 x 0.2)/ 153 = 104.

At December 1998, the Atlantic network in Glasgow had 43 base stations, implying a potential total of 43 x 6 = 258 sectors. This is two and a half times the "idealised" minimum requirement calculated above and would provide sufficient capacity for 56,000 residential subscribers at 70 millierlangs per subscriber, a penetration rate of just over 10% of the total population of the Glasgow City area. It is therefore reasonable to assume that the current Atlantic network in Glasgow, when fully loaded, represents a realistic model of a mature RFA POTS network with relatively high penetration.

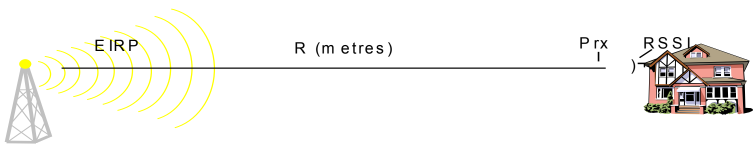
The distribution of base stations, even within the Glasgow area, is not uniform but varies according to the local business and residential population density. Atlantic advise that currently their base stations serve a radius of typically 1 -1.25 km. Allowing for a degree of overlap to ensure contiguous coverage, this approximates to a density of 1 base station per km^2 in the most populated areas. It is possible that capacity enhancement may be needed in certain areas to cater for growth in data traffic, in which case the density of base stations may increase in certain areas (see also section 3.1.4 below concerning the impact of wideband and broadband data services on network capacity).

[10] Based on the penetration level in Glasgow City claimed by Atlantic Telecom at December 1998

[11] Glasgow City population (1991 Census)

3.1.3 Interference considerations

As noted above, an RFA network must substantially match the performance and availability levels of wire line networks. In practice this means that the transmission power budget must include a sufficient margin to overcome transient interference levels which may otherwise lead to system outages. The power budget of an RFA link between network base station and subscriber station is defined as follows



$$RSSI\ (dBm) = EIRP\ (dBm) - FSPL\ (dB) + G_{rxant}\ (dB)$$

where

RSSI = Received Signal Strength Indicator (power received at the subscriber receiver)

EIRP = Effective Isotropically Radiated Power from the network base station

FSPL = Free Space Path Loss between the two stations (20 log $4\pi R/\lambda$)

G*rxant* = Gain of the subscriber receive antenna

In the UK, RFA systems using the 2.4 GHz frequency band must comply with ETS 300 328 and CEPT Recommendation 70-03, which stipulates a maximum EIRP of -10 dBW.

The Atlantic network uses the "Multigain" FHSS wireless technology, developed and supplied by the Israeli company Innowave. Multigain allows the network operator to programme individual frequency hopping sequences and if necessary to exclude parts of the 2.4 GHz band which are prone to interference. In Glasgow, Atlantic uses 54 of the available 79 frequencies. A frequency re-use factor of 3 means that up to 18 hop sequences per sector are available.

The principal RF parameters of the Atlantic systems are:

Base Station antenna gain:	11 dBi
Subscriber station antenna gain:	14 dBi
Planned RSSI level at base station:	-105 dBW
RSSI threshold for zero WER[12]	-115 dBW
RSSI threshold for 1% WER	-125 dBW

The above RSSI thresholds assume a noise limited environment where external interference

[12] Word Error Rate

is negligible. RFA networks typically operate in an interference limited environment where interference arises from other transmitters within the RFA network and from external sources such as (at 2.4 GHz) RLANs and ISM equipment. The transmitted RFA signal may also be subject to fading due to reflections from buildings, trees, vehicles or other objects that lie on or near the antenna beam. These factors require an additional "link margin" to be added to the transmitted EIRP which would otherwise be sufficient to deliver the above RSSI levels under ideal free space propagation conditions.

Atlantic aim to provide a margin of at least 20 dB above the nominal RSSI threshold level for 1 % WER for business subscribers and at least 15 dB for residential subscribers. Subscriber stations are therefore configured to deliver a measured RSSI at the nearest base station of –105 dBW (business) or –110 dBW (residential) and the EIRP is set accordingly. Base stations are run at the maximum permissible -10 dBW EIRP, although this could be reduced for some future installations if greater frequency re-use was required. All paths between subscriber and base stations are line of sight.

It follows that the RSSI at the subscriber station will in most cases exceed the 1% WER level by a substantial margin, the precise value of which will depend upon the distance between base and subscriber station, as shown in table 3.1 below:

Distance from Base Station (metres)	RSSI (dBW)	EIRP (dBW)
100	-76.3	-35.7
500	-90.3	-21.7
1000	-96.3	-15.7
1250	-98.3	-13.7

Table 3.1 RFA subscriber station EIRP and RSSI levels as a function of distance from the base station

Actual RSSI levels, as determined during joint Atlantic Telecom / RA monitoring exercises, are typically between –110 and –120 dBW, suggesting the link margins applied are perhaps erring on the low side. The network is planned to a minimum carrier to interference ratio (C/I) of 15 dB, although in practice stations are found to work satisfactorily with C/I levels as low as 10 dB. For the purposes of modelling, an upper limit on interference at the receiver input of -125 dBW has been assumed for the network is to perform acceptably with its current configuration.

If interference exceeds this level, performance may be recovered by increasing the link margin between subscriber and base stations, i.e. increasing the subscriber station EIRP. However, the regulatory upper limit on EIRP is -10dBW, which is only 3.7 dB above the EIRP required at 1.25 km to provide an adequate RSSI. Any significant increase in the link margin to overcome extraneous interference would therefore reduce the maximum cell size and require replanning of the network.

In a practical RFA network interference is minimised by the use of sectored, downtilted base station antennas. For the purposes of this study it has been assumed that all RFA base station antennas have nominal 3 dB beamwidths of 60^{o} and are downtilted at an angle of 12^{o} below the horizontal.

3.1.4 Wideband and Broadband Services

Wideband digital telecommunication services are those running at bit rates between 64 kbit/s and 2 Mbit/s, broadband services are those running at > 2 Mbit/s. Whilst the great majority of telephone services are still narrowband, there is increasing user demand for wideband and broadband access, both among businesses and residential consumers. Wireline operators are already addressing the wideband market with services like ISDN and Home Highway, which can deliver 128 kbit/s or more via the existing copper local loop. Advanced trials of Digital Subscriber Line (DSL) services are also underway which promise to deliver broadband bit rates via existing lines, with interest focussing on the provision of high quality real time video.

If they are to remain competitive in the longer term, it will be important for RFA operators to be able to match these wideband and broadband offerings. Licences have been issued in the 10 GHz band specifically for the provision of ISDN and other wideband offerings. However, operators like Atlantic Telecom who exclusively operate in the 2.4 GHz band will require a means to deliver these services using their existing spectrum.

Atlantic Telecom has already announced its intention to trial a new generation of 2.4 GHz FHSS high speed data technology using equipment supplied by another Israeli company, RDC Communications. The new technology is based on RDC's Wireless Internet Protocol Local Loop product (WipLL) which can deliver up to 4 Mbit/s per radio link, or 64 Mbit/s per base station by co-locating multiple transceivers. As well as delivering high speed data, WipLL can also deliver toll quality voice and claims to provide improved spectrum utilisation by use of proprietary dynamic channel assignment (DCA) algorithms.

Meanwhile Innowave, the supplier of the current Atlantic narrow band system, has announced it is developing a wideband version using DSSS based on the IEEE 802.11 physical layer (see section 3.2.2). This would deliver bit rates between 64 kbit/s and 8 Mbit/s per base station sector and would dynamically handle and prioritise voice and data calls. Up to 24 sectors per site would be realisable using configurable-beam antennas.

These developments do not necessarily mean there will be a significantly greater demand on spectrum resources. Broadband packet switched networks only transmit when information is actually being conveyed, whereas conventional circuit switched RFA networks transmit continuously in each direction while a call is in progress. This means that the efficiency of a packet switched network can be significantly higher for a given data throughput, particularly for internet browsing where there is a high degree of latency and asymmetry. Until recently packet switched networks have not been suitable for real time applications such as voice telephony, but recent improvements to the protocols used for delivering voice over IP make the provision of toll quality voice over packet switched networks increasingly feasible.

Taking these factors into account, it is difficult to compare directly a conventional voice network dimensioned in erlangs with a packet switched network. A significant proportion of wideband real time traffic (such as high quality video) could lead to a much higher total capacity requirement than at present. For interference modelling purposes allowance has been made for this by considering a significantly greater density of base stations (up to 10 per km^2, which would represent a 10 fold increase in capacity relative to the current Atlantic network configuration).

3.2 Radio Local Area Networks (RLANs)

3.2.1 RLAN Standards

In the UK, all RLANs must conform to the regulatory type approval standard ETS 300 328 and CEPT Recommendation 70-03, which define RF emission limits for FHSS and DSSS systems (sections 2.1.1 and 2.1.2). Recently proposals have been put to CEPT to increase the current EIRP limit of 100 mW to 500 mW. Our analysis has been based on the deployment of 100 mW devices; should the EIRP be increased to 500 mW in the future it will be necessary to add up to 7 dB to the projected interference levels originating from RLAN devices.

Over the years many proprietary ETS 300 328 compatible standards have emerged, however more recently there has been a trend towards adoption of an internationally recognised interoperability standard developped by the US based Institution of Electrical and Electronic Engineers (IEEE). This emergence of this interoperability standard, designated IEEE 802.11, enables users to multiple source RLAN components from different suppliers and has led to renewed growth in the market for RLAN products. Although other proprietary standards are likely to co-exist alongside IEEE 802.11 for the foreseeable future, it is anticipated that the majority of new products shipped in the future will be IEEE 802.11 compliant. In terms of their RF parameters there is little difference between IEEE 802.11 and other 2.4 GHz RLANs, hence our interference analysis is based on the assumption that all RLANs are compliant with the IEEE standard.

IEEE 802.11 defines two types of network protocol. The *ad-hoc* protocol caters for simple interconnection of network elements where there is no central access point or server. Each interconnected element must observe an etiquette to ensure that each has fair access to the available radio spectrum. This involves monitoring the channel to determine whether it is clear of interference before proceeding with transmission. The *client / server* protocol uses a central access point (server) to control the allocation of radio spectrum resource to the various interconnected elements. The access point also allows traffic to be routed to or from different “cells” within a network, enabling mobile network elements to roam over a much wider area than would be the case for a simple, single cell network or point to point link. In radio interference terms, client / server networks will generally be larger and carry more traffic, hence will pose a greater interference risk.

Most RLANs are configured on the client/server principle and comprise one or more cells within which individual computers or peripherals communicate with each other under the supervision of an Access Point (AP). The number of wireless stations each cell can accommodate depends on the nature of the traffic between them, but is typically in the range 50 – 200. All traffic within the cell is managed via the AP. If required, cell APs may themselves be connected using a 2.4 GHz radio link, known as a *wireless bridge*. Adjacent cells may overlap, allowing users to roam between them in a similar manner to mobile phones on a cellular network. Overlapping cells can also be used to provide increased capacity in busy locations and to provide diversity in the event of interference or congestion on a specific cell. Within a given cell, radio transmissions are continuous from the central access point and distributed among the terminals in line with the data traffic distribution.

IEEE 802.11 defines two RF physical layers, namely FHSS and DSSS. Currently, just over 50% of new RLAN systems are based on FHSS. A recent report by Frost and Sullivan[13] estimated that the proportion of spread spectrum RLANs using FHSS technology would increase to 68% by the year 2003. The remainder would be DSSS. Most of the major manufacturers and suppliers of RLANs are committed to one or other of these technologies (see section 4.5.2), although some offer both. Generally, FHSS is considered better at supporting a dense population in a small area, because it has more independent RF channels, whilst DSSS Provides greater operating range and coverage area (because it can operate with a lower carrier to noise ratio) and enables greater data throughput.

3.2.2 FHSS RLANs

IEEE 802.11 defines the following characteristics for FHSS RLAN systems:

No. of RF channels:	79
No. of hop sequences:	78 (3 sets of 26)
RF Channel bandwidth:	1 MHz (20 dB)
Minimum freq sep between consecutive hops:	6 MHz
Minimum Hop Rate:	as specified in ETS 300 328
Maximum data rate:	3 Mbit/s (over the air)
Receiver Sensitivity[14]:	-113 dBW (1 Mbit/s, 2 FSK) -105 dBW (2 Mbit/s, 4FSK) -97 dBW (3 Mbit/s, 8FSK)

Table 3.2 Principal characteristics of IEEE 802.11 RLANs

Channel centre frequencies are 2402.0 – 2480.0 MHz inclusive, at 1.0 MHz intervals. Hopping sequences from the same set collide three times on average, five times worst case over a hopping cycle, including co- and adjacent channel collisions. All hopping sequences are derived from a common base sequence, by incrementing the frequency of each hop by *k*, where k = 1, 2, 3,…78.

The 78 available hop sequences are sub-divided into three groups of 26. Within each group, the 26 sequences are orthogonal to one another (i.e. there will be no co-channel or adjacent channel frequency collisions), allowing systems to be co-located with minimal interference. In

[13] "World Wireless LAN Markets", report no 5781-74, Frost & Sullivan, 1999.

[14] Source: Breezenet PRO.11 data sheet

practice, however, this orthogonality is compromised since independent systems are not synchronised. This places a practical upper limit on the number of FHSS systems which may be co-located (e.g. within a single building) of 15, although some suppliers suggest that up to 22 systems can be co-located without any appreciable degradation of performance. Co-located FHSS systems need not be synchronised unless they are deployed for real time applications such as voice.

FHSS systems can tolerate a significant amount of in-band interference providing this only affects part of the available spectrum. For example, if 25% of the available hop frequencies are unusable due to interference, the FHSS systems will still operate at 75% of its capacity. The effect of interference on FHSS systems is further mitigated by the requirement in 802.11 for consecutive hops to be separated in frequency by at least 6 MHz, minimising the chances of narrow band interference affecting two consecutive hops.

The 1 MHz individual RF channel bandwidth limits the over the air data rate of FHSS systems to 3 Mbit/s (with 8FSK modulation). Higher data rates require either collocation of multiple FHSS systems or the use of DSSS technology with a higher level modulation scheme.

3.2.3 DSSS RLANs

Although there are a number of proprietary DSSS systems on the market, there is an increasing trend towards compliance with the IEEE 802.11.

The principal characteristics of the 802.11 DSSS physical layer are:

- Spreading sequence: 11 bit Barker code
- Coding gain: 10.4 dB
- Maximum Data Rate: 11 Mbit/s
- RF Bandwidth 30 MHz
- Receiver Sensitivity: –70 dBm (10^{-5} BER)[15]
- Adjacent channel rejection: >35 dB

IEEE 802.11 defines nine DSSS carrier frequencies for use in Europe. These are (MHz):

2422	2427	2432	2437	2442	2447	2452	2457	2462

[15] Figure quoted by Harris Semiconductors for its 11 Mbit/s chip set; lower bit rate systems will have greater sensitivity.

The transmitter spectrum mask is defined thus:

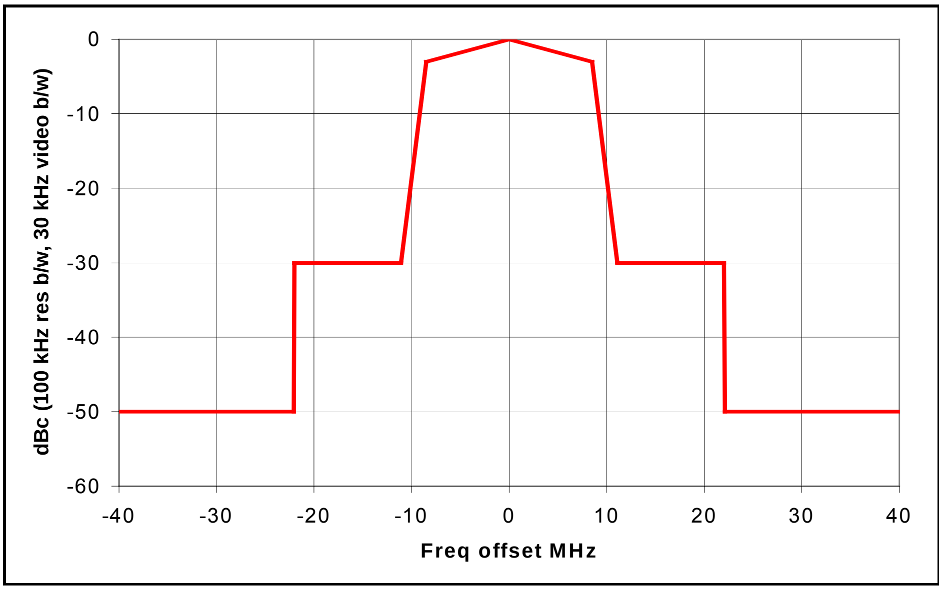


Figure 3.1 Transmit spectrum mask for IEEE 802.11 DSSS physical layer

The 11 bit Barker code was chosen on the basis of its excellent autocorrelation properties. By producing a single peak and uniformly low sidelobes when correlated against time shifted versions of itself, the code minimises the effect of multipath interference in indoor environments. Unfortunately the code does not provide sufficient coding gain to allow effective CDMA operation, as the coding gain is of the same order as the E_b/N_0 level required to achieve satisfactory bit error rates. Consequently a minimum S/N ratio in the spread bandwidth of 0 dB (BPSK) or 3 dB (QPSK) is required, ruling out anything other than two equal power BPSK systems to be co-located on the same channel. However, the ability to work with very low S/N ratios and correspondingly low C/I ratios means systems can be operated up to 10 dB closer together than other non-spread systems, all other things being equal.

The current 802.11 DSSS standard caters for bit rates of 1 Mbit/s and 2 Mbit/s, using BPSK and QPSK modulation respectively.

Work is advancing in the IEEE 802.11 standards group on the introduction of higher level modulation schemes that will increase data rates to 11 Mbit/s. It is intended that these higher level schemes will be fully interoperable with the existing 802.11 protocols, enabling automatic rate switching in the presence of noise or interference. One of the favoured modulation schemes for these higher data rates is a form of Cyclic Code Keying (CCK), which uses 8-level modulation to remain within the above spectrum mask. Other schemes under consideration include OFDM, where the data is transmitted on multiple narrow band channels spaced at regular intervals, modulated with PSK. To facilitate co-existence between different systems, all modulation schemes must comply with the above spectrum mask.

The minimum C/I requirement to achieve a good BER performance (10^{-5}), according to data published by Harris Semiconductors is:

1 Mbit/s BPSK:	0 dB[16]
2 Mbit/s QPSK	3 dB
5.5 Mbit/s CCK/BPSK	4.6 dB[17]
11 Mbit/s CCK/QPSK	7.8 dB[5]

Tests conducted by Harris show that in the presence of delayed multipath interference, the worst case 10^{-5} BER C/I level for an 11 Mbit/s DSSS receiver is 11.5 dB. This was for a multipath interferer delayed by 1 chip period, where there is a high degree of correlation between the wanted and interfering signal. The mean value over a range of delay periods (which is more representative of a typical operating environment) was 8 dB, consistent with the figure quoted above

DSSS systems can thus tolerate a higher overall level of interference within their operational band, however as they operate in a narrower frequency band than FHSS systems they may be more susceptible to narrow band interference. DSSS systems may be blocked by other nearby DSSS systems if these transmit on the same frequency and are not synchronised.

The modular nature of many RLANs means that upgrading from existing 1 or 2 Mbit/s systems to 5.5 or 11 Mbit/s is feasible, simply by replacing the baseband processor. High bit rate systems are able to step down to lower level modulation schemes and operate at a lower speed in the presence of interference or when received signal levels fall below the required threshold.

3.2.4 Multiple Access Control (MAC)

Regardless of whether FH or DS is deployed, a protocol is required to ensure that reliable transmission takes place even in a hostile RF environment. This protocol is defined in the MAC physical layer of the IEE 802.11 standard and is known *carrier-sense, multiple access, collision avoidance* (CSMA/CA). The purpose of the protocol is to avoid data collisions, such as might occur if two FHSS network elements simultaneously transmit on the same hopping channel. This is achieved by continuous monitoring of the received signal strength indicator (RSSI) level at each receiver terminal. Transmission on a particular frequency is only allowed to proceed if the RSSI is below a certain threshold level. If the threshold level is exceeded, transmission is deferred and transmitted on the next clear channel. This process is known as clear channel assessment (CCA). CCA typically requires a level of –85 dBm or less to be present for transmission to proceed.

An alternative approach to CCA is **carrier sense**, which detects whether or not another 802.11 signal is present on the channel. If no 802.11 signal is present, transmission will proceed regardless of RSSI level, relying upon there being an adequate link margin to

[16] Carl Andren, “Short PN Sequences for DSSS Radios”, Harris Semiconductors Technical Brief, November 1997

[17] Carl Andren, “11 Mbit/s Modulation Techniques”, Proceedings of the Sixth Annual Wireless Symposium, February 1998, p.142

overcome any extraneous interference at the receiver. The choice of approach depends upon the level of interference in the operating environment – carrier sense is preferred in harsh environments because it can distinguish between RLANs and other interferers.

Within a single RLAN system, the CSMA/CA protocol avoids collisions by initiating “request to send” (RTS) signals which include details of the message length and intended destination within the network. This causes other transmitters in the network to avoid transmission on that hop sequence for the duration of the transmitted message. The protocol also provides acknowledgement signals to verify that data has been received by the intended recipient.

3.2.5 Wireless Bridges

An increasingly common application of 2.4 GHz RLAN technology is its use to link together conventional LANs on remote sites. Wireless bridges, as such systems are known , provide point to point or point to multipoint connectivity between sites using rooftop mounted directional or omnidirectional antennas. Ranges of 10 km or more have been achieved over line of sight paths and a variety of applications are already being addressed in the UK (see section 3.2.7)

3.2.6 Indoor RLAN applications

According to major suppliers, RLANs are perceived as complementary to, rather than replacements for, wired LAN systems. Typical applications include:

- extensions of wired networks into areas where cabling may be impractical or prohibitively expensive
- campus based organisations spread over multiple buildings
- temporary accommodation
- construction sites
- retail outlets
- schools and colleges
- hospitals

Terminals may be implemented as stand alone desktop devices or as plug in PCMCIA cards for desktop PCs, laptops, or handheld personal digital assistants (PDAs). Although they can be deployed in indoor or outdoor locations, they are particularly suited to indoor situations where the shielding provided by the building structure and internal furniture increases the frequency re-use.

A common application in the UK is in Electronic Point of Sale (EPOS) systems in supermarkets and department stores. Although the data rates required for this application are somewhat lower (typically < 100 kbit/s) than in a typical office or academic environment, error free transmission is paramount, necessitating a high degree of processing gain or error correction. Over the air data rates are thus comparable to those generated by RLAN systems. Similar systems are also being installed in banks and other financial institutions where the inherent security offered by spread spectrum transmission is seen as an additional benefit.

An example of an EPOS application is Littlewoods' Stores Ltd, which has chosen a radio based system supplied by Lucent subsidiary WaveLAN for its 130 UK stores. A typical store has 18 EPOS terminals connected to 1 or more access points. The benefits cited by Littlewoods' include simplified rollout, configuration flexibility and cost savings on installation. Suppliers of radio based EPOS systems also highlight their ability to interface with stock control systems, using hand held bar code scanners to monitor stock levels and movements

Global engineering and construction company Halliburton Brown and Root has installed an indoor office RLAN system at its Leatherhead offices, to extend the company's Ethernet network to mobile users anywhere on the second and third floor of the building. The system comprises 10 APs connecting 100 notebook PCs equipped with RLAN PCMCIA cards.

3.2.7 Outdoor RLAN applications

Although fewer in number, outdoor systems are likely to have a disproportionate effect on cumulative interference levels because of the lack of building attenuation. The following examples have been identified which illustrate how RLAN technology can be used to provide connectivity between remote sites:

i) Stevenage Borough Council

An extensive outdoor system has been installed in Stevenage, Herts., to interconnect LANs in nine separate council premises within a 25 km^2 area around the town centre. A total of 150 PCs are connected to the network via rooftop mounted wireless bridges supplied by Breezecom. The network includes three repeater stations to overcome terrain obstacles. The system has been running since early 1998 and provides a continuous flow of data between the interconnected sites. The network delivers a 3 Mbit/s transfer rate between sites and over 20 Mbit/s aggregate throughput. The system comprises six access points, nine wireless bridges and four multi-port terminals (radio terminals capable of connecting up to 4 PCs). Antennas are either directional (18 or 24 dBi) or omnidirectional (10 dBi). A similar system has recently been installed by Harlow Borough Council and other local authorities are understood to be considering similar wireless networks. The principal benefit is cost saving over conventional leased lines.

ii) Lancaster University Schools' Internet Service

EDNET (EDucational NETwork) is a network providing Internet access to schools and other educational establishments in the Lancaster and Morecambe (Lancs) district. It uses 2.4 GHz DSSS technology supplied by WaveLAN. The network currently has a data bandwidth of 2Mbit/s that is shared by all organisations using the network, but there are plans to upgrade this to 11 Mbit/s in the future. Currently 13 sites are connected to a central server at Lancaster University, c. 3 km south of the town centre.

iii) Red Funnel Ferries, Southampton

This is an example of a mobile outdoor application of 2.4 GHz RLAN technology. Directional antennas situated at the ports at Southampton and Cowes, Isle of Wight enable data communication between ferries and the ports, via a 10 dBi omnidirectional antenna on the ferry. The link takes the form of a FHSS wireless bridge supplied by Breezecom. This is a somewhat rare example of a mobile outdoor system in the band.

Some manufacturers claim that up to 50% of their shipments in UK are outdoor systems.

3.2.8 Interference Considerations

The following RLAN receiver parameters (based on IEEE 802.11 physical layer and suppliers' data) have been assumed for interference assessment purposes:

Type	Rx Sens (10^{-5} BER)	Min C/I (10^{-5} BER)	Max interference	Notes
FHSS 1 Mbit/s	-110 dBW	15 dB	-125 dBW	1 MHz b/w
FHSS 2 Mbit/s	-105 dBW	20 dB	-125 dBW	1 MHz b/w
DSSS 1 Mbit/s	-110 dBW	0 dB	-110 dBW	22 MHz b/w
DSSS 2 Mbit/s	-105 dBW	3 dB	-108 dBW[18]	22 MHz b/w
DSSS 5.5 Mbit/s	-105 dBW	5 dB	-110 dBW	22 MHz b/w
DSSS 11Mbit/s	-100 dBW	8 dB	-108 dBW	22 MHz b/w

Table 3.3 RLAN receiver parameters

The transmit EIRP is –10 dBW for all access points and terminals, hence many receivers will operate with a significant interference margin. Higher capacity RLAN systems typically "back off" to lower bit rates prior to failing altogether. The effect of interference will be to progressively reduce the range at which this occurs.

Most internal RLAN receivers use omnidirectional antennas, which may be single element (2 dBi gain) or twin element (5 – 8 dBi gain) dipoles. This relatively low antenna gain and the additional attenuation associated with indoor operation makes indoor RLAN systems less susceptible to interference than RFA systems with their relatively high gain antennas.

Outdoor RLANs and wireless bridges may deploy directional antennas with gains as high as 24 dBi, to extend coverage range. Such systems may suffer serious interference if their antennas are aligned with an interference source. But conversely are less likely to be affected by multiple interferers than receivers with omnidirectional or sector antennas.

3.3 Other Wireless Connectivity Systems

3.3.1 Bluetooth

"Bluetooth" is the code name for a global wireless connectivity standard being developed by a heavyweight consortium of IT and telecommunications companies including Ericsson, Motorola, Nokia, IBM and Intel. The Special Interest Group (SIG) backing the standard now has over 500 members worldwide, including all the major suppliers of 2.4 GHz RLANs. Its objective is to replace the plethora of proprietary cable links that currently connect IT and telecom devices to one another and replace them with a single universal short range radio

[18] = -121 dBW / MHz

link. Unlike existing infra-red wireless links, Bluetooth would not require a clear line of sight path between the two devices and would, for example, allow an e-mail to be sent from a laptop PC via a mobile phone, which might be in the user's jacket pocket or briefcase. All that would be necessary is for the two devices to be within the Bluetooth transmission range, which is intended to be up to 10 metres for most applications.

Bluetooth uses FHSS to ensure robust performance in a noisy radio environment. According to the SIG, the standard uses shorter and faster hops than other 2.4 GHz FH systems and is consequently more robust. This will be important, as it is highly likely that Bluetooth will be used alongside more powerful RLAN systems using the same spectrum. Bluetooth can support both voice and data, up to a gross data rate of 1 Mbit/s. Up to eight devices or three voice channels may be connected simultaneously to a single "piconet", in which all are synchronised to a single hopping sequence, and up to ten of these "piconets" may be interconnected at a single location, each using a different hop sequence.

The Bluetooth air interface is designed to be compliant with international standards, including ETS 300 328, but in general will operate at a lower power level of 1 mW EIRP (although the standard allows for variants up to 100 mW). Instantaneous bandwidth is 1 MHz, allowing a total of 79 hop frequencies within the 2.4 GHz band. Of these, 32 are used by any individual "piconet". The maximum hopping rate is 1600 hops/sec.

The Bluetooth air interface is based on a nominal antenna power of 0dBm. The air interface complies with the FCC rules for the ISM band at power levels up to 0dBm. Spectrum spreading has been added to facilitate optional operation at power levels up to 100 mW worldwide. Spectrum spreading is accomplished by frequency hopping in 79 hops displaced by 1 MHz, starting at 2.402 GHz and stopping at 2.480 GHz.

The maximum frequency hopping rate is 1600 hops/s. The nominal link range is 10 centimetres to 10 meters, but can be extended to more than 100 meters by increasing the transmit power.

For the purposes of interference modelling an interference limit of –80 dBm in a 1 MHz bandwidth is assumed, i.e. equivalent to the CCA threshold for IEEE 802.11 RLANs. This limit would ensure a minimum 20 dB C/I ratio at an unobstructed distance of 10 metres. Antennas are assumed to be omnidirectional with 0 dBi gain.

3.3.2 HomeRF

The "HomeRF Working Group" is another international consortium which is developing a global "shared wireless access protocol" (SWAP) for interconnecting IT and telecommunications equipment in the home. Although many of those in the Bluetooth SIG are also active members of the HomeRF Group, the latter has a greater representation from the IT industry. Companies such as IBM, Compaq and Microsoft are all actively developing SWAP based products for the home, with expectations of launching the first products by the end of 1999. There are currently 70 members in total.

A wide range of applications is foreseen, beyond the mere interconnection of PC peripherals. One example cited by the group is the delivery of Internet data to mobile display terminals, which could be used to display recipe information in the kitchen or DIY information in the garage. SWAP will also support voice, and is compatible with the DECT Generic Access Profile (GAP) for digital cordless phones. As an open, royalty free standard, SWAP may well succeed in displacing existing cable based connections, particularly if supplied as a standard component of new PC systems.

SWAP is designed to carry both voice and data traffic and to interoperate with the PSTN and the Internet. It supports TDMA to provide delivery of interactive voice and other time-critical services, and CSMA/CA for delivery of high speed packet data.

The Main System Parameters are:

- Frequency hopping rate: 50 hops/second
- Frequency range: 2400 – 2483.5 MHz
- Transmit EIRP: 100mW
- Data Rate: 1 Mbit/s (2FSK)
  2 Mbit/s (4FSK)

In the future, HomeRF promises a higher data rate of 2 Mbit/s burst compared with 1 Mbit/s for Bluetooth, which will result in a sustained data rate on the order of 300 to 500 kbit/s. Bluetooth is also specified for transmission over short distances (up to 10 metres) while HomeRF is intended to cover typically a 100-metre range. Unlike Bluetooth, HomeRF is IEEE 802.11 compliant.

SWAP can support up to 127 devices and 6 full duplex conversations per network A 48-bit network ID code enables concurrent operation of multiple co-located networks.

As with RLANs, SWAP systems can operate either as ad-hoc networks or as a managed networks under the control of a Connection Point (analogous to an RLAN AP). In an ad-hoc network, where only data communication is supported, all stations are equal and control of the network is distributed between the stations.

For time critical communications such as interactive voice, a Connection Point is required to co-ordinate the system. The network can accommodate a maximum of 127 nodes. These nodes can be a mixture of four basic types:

- Connection Point that supports voice and data services
- Voice Terminal that only uses the TDMA service to communicate with a base station
- Data Node that uses the CSMA/CA service to communicate with a base station and other data nodes
- Voice and Data Node which can use both types of services

For the purposes of interference modelling an interference limit of –110 dBW in a 1 MHz bandwidth is assumed, i.e. equivalent to the CCA threshold for IEEE 802.11 RLANs. Antennas are assumed to be omnidirectional with 0 dBi gain.

4 PROJECTED MARKET PENETRATION AND USER DENSITY

4.1 RFA

It is reasonable to assume that a successful RFA operator would seek a long term local market penetration of at least 10 per cent. Although this seems a modest figure, the challenge in terms of persuading subscribers to migrate from existing wire line providers should not be underestimated. Should regulatory policy towards third party access to the BT local loop change, this could make radio provision less attractive, as it may be more economic simply to provide access via the existing copper loop. In the longer term, migration towards higher bandwidths and the need to compete with digital subscriber line technologies (DSL) will also mitigate against the widespread roll out of narrow band RFA. Atlantic have already pre-empted this development by announcing the introduction of wideband RFA services, a development which may have a significant bearing on spectrum capacity and interference levels at 2.4 GHz.

Section 3.1.2 suggested that a base station density of 1 per km^2 would be representative of a mature urban network, based on 10% long term market penetration. However, to allow for future traffic growth or capacity enhancement (such as the introduction of broadband data services), we have also modelled scenarios with 3 and 10 base stations per km^2, the latter being considered a realistic "worst case" scenario.

4.2 RLANs

The advent of the IEEE 802.11 standard has done much to stimulate the global market for RLAN products. There are a number of major manufacturers, each of which tends to concentrate on particular segments of the market.The principal suppliers addressing the UK market include:

Company	Origin	Technology	Main applications	Notes
Aironet / Telxon	USA	Predominantly DS	Retail, manufacturing, warehouses, mobile office	Aironet subsidiary currently being floated by parent company Telxon
Breezecom	Israel	FH	Wireless bridges, mobile office	
Lucent	USA	DS	Education, retail	Has recently expanded into the outdoor system market by acquisition of

				WaveAccess
Proxim	USA	FH	Education, Health, SOHO, RFID	
Symbol	USA	FH	Retail, warehousing	

Table 4.1 Major RLAN suppliers in the UK

A recent market forecast study produced by International Data Corporation[19] concluded that there would be continuing steady growth in the global RLAN market over the next four years, with annual growth in total shipments of over 30%. The total installed base of radio terminals was forecast to grow from 866,000 in 1997 to over 12 million in 2003. Of these, 81% are projected to be Network Interface Cards (i.e. connections to individual PCs or hand held terminal), 17% access bridges (i.e. interfaces with wired systems) and 2% building to building bridges. If each access bridge is considered to represent a single indoor system, this implies that globally by 2003 there will be c. 2.04 million indoor RLAN systems and 240,000 outdoor systems. A separate market study by Frost and Sullivan[20] forecasts that the proportion of total installed RLAN base using DSSS will decline from 43% in 1997 to 32% in 2003.

Discussion with UK based representatives of major suppliers indicates that some anticipate a significantly higher proportion of outdoor systems, with two in particular indicating that outdoor systems account for up to 50% of their UK shipments. Other suppliers, notably those more rooted in the retail and warehousing sector, supply almost exclusively indoor systems. On the basis of published material and discussions with UK based supplier representatives, we have concluded that the likely proportion of UK based RLAN systems which will be located outdoors is between 10 and 20 %. The higher figure is based upon a significant level of deployment for internet service provision, whereas the lower figure assumes outdoor systems will be limited to private or closed user group applications.

The total size of the UK market for RLAN systems has been estimated, on the basis of discussion with suppliers and consideration of world demographic statistics, at 3 -4 % of the total global market for this type of device. Assuming 4% would suggest an installed base of RLAN systems by 2003 of 91,000 systems, based on the IDC estimate of the global market size. Outdoor systems would amount to 9,000 - 18,000 depending upon whether they are assumed to be 10% or 20% of total UK RLAN installations.

Discussion with suppliers has indicated that over the next 3 – 5 years up to 25% of installed LAN systems may include some form of radio element. In most cases the radio part will probably complement an existing wired installation or, for outdoor systems will comprise wireless bridges linking individual LAN systems in separate buildings. Some RLANs will however be complete stand alone networks, notably in the banking and retail sectors and in

[19] "Wireless LANs: Worldwide Market Review and Forecast, 1997 - 2003", IDC, June 1998.

[20] "World Wireless LAN markets", Frost and Sullivan report no. 5781-74, 1999

situations involving temporary office accommodation, such as large construction sites.

Assumptions for Modelling

For interference modelling purposes, a number of RLAN penetration scenarios have been considered, representing various combinations of indoor and outdoor systems in urban, suburban and rural environments (section 4.6 summarises the specific scenarios addressed). Account has also been taken of various mixes of FHSS and DSSS systems. Penetration levels have been estimated on two bases, namely the above IDC forecast data and our own empirical estimates based upon typical geographic distribution of commercial and business premises.

The financial centre of the City of London (the "square mile") has been chosen as a hypothetical worst case interference scenario. The geographic density of RLANs deployed in the City by the year 2003 has been determined by considering the following statistics:

Total UK employment base:	28.5 million
Proportion employed in relevant sectors[21]:	56%
Total employed in relevant sectors:	16 million
Total employed in the City of London:	250,000[22]
Proportion of UK total based in City of London:	1.56%
Indoor RLANs in the City of London (1.56% of UK total):	1,279
Total area of the City of London:	3.15 km^2
Density of RLANs in the City of London	406 per km^2

A more typical mixed urban scenario can be determined by repeating the above calculation for the London Borough of Camden and for the cities of Manchester and Glasgow (central areas). In these cases the estimates of the number employed is based on the proportion of the total UK population resident in those areas. Finally, the town of Stevenage, Herts was considered as a typical medium sized provincial town. In each case the number of people employed within the area in relevant sectors was assumed to be 56% of the total working population in the area plus an equal number to allow for those commuting into the area on a daily basis.

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[21] The following OECD employment categories are considered relevant in terms of their likely use of RLAN systems:

Wholesale and Retail Trade

Transport storage and communication

Finance insurance and business services

Producers of Government Services

[22] For the purposes of this worst case scenario it is assumed that all those working in the City are employed in relevant sectors.

London Borough of Camden:

Total employed in relevant sectors in UK:	16 million
Total employed in the LB of Camden:	92,000
Proportion of UK total based in LB of Camden:	0.28%
Indoor RLANs in LB of Camden (0.28% of UK total):	230
Total area of the LB of Camden:	22 km^2
Density of RLANs in the LB of Camden	**21 per km^2**

Manchester (City):

Total employed in relevant sectors in UK:	16 million
Total employed in the City of Manchester:	260,000
Proportion of UK total based in Manchester:	1.62%
Indoor RLANs in the Manchester (0.81% of UK total):	1,328
Total area of Manchester:	110 km^2
Density of RLANs in Manchester:	**12 per km^2**

Glasgow:

Total employed in relevant sectors in UK:	16 million
Total employed in the City of Glasgow:	424,000
Proportion of UK total based in Glasgow:	2.65%
Indoor RLANs in Glasgow (4% of UK total):	2,173
Total area of the Glasgow:	197 km^2
Density of RLANs in Glasgow:	**11 per km^2**

Stevenage:

Total employed in relevant sectors in UK:	16 million
Total employed in Stevenage:	21,500
Proportion of UK total based in Stevenage:	0.14%
Indoor RLANs in Stevenage:	115
Total area of Stevenage:	25 km^2
Density of RLANs in Stevenage:	**4.6 per km^2**

For the purposes of assessing the interference into a wide area system such as an RFA network, with cell sizes of the order of 1 km or more, it is reasonable to assume a uniform distribution across these urban areas. However in practice it should be noted that certain location such as shopping or business centres will have higher concentrations, up to 2 - 3 times the densities quoted above (this does not apply to the City of London where the whole area falls into this category.

The following indoor RLAN densities have been modelled, representing typical urban, suburban and rural densities based on the above statistics. Stevenage is assumed to be representative of a typical suburban area, while a nominal density of 1 system per km^2 has been assumed for rural areas.

Type of area	Low penetration	Med penetration	High penetration
Dense urban	200	400	800
Urban	10	20	40
Suburban	2.5	5	10
Rural	-	-	1

Table 4.2 Indoor RLAN densities used in the simulations (systems per km^2)

Initially we have also assumed that the split between and FS and DS systems will reflect the 68% - 32% DS proportion forecast by Frost & Sullivan, however the medium penetration scenarios have also been repeated with an alternative mix where DS RLANs make up the majority (60%) of installations.

For outdoor systems we have assumed a more uniform geographic spread, roughly in line with population density. This reflects the likelihood that they will be predominantly used to link remote sites in areas where there are not ready alternatives to radio, which will tend to be outside the centres of major conurbations. On this basis, taking the higher projected figure of 20,000 total installations in the UK and assuming that the proportion of these in the main conurbations is in line with the proportion of the UK population in that region, we have determined the density of links in specific regions as :

Conurbation	Population	Area (km^2)	No of systems	Density (per km^2)
Manchester	455,000 (0.81%)	110	162	1.5
Glasgow	744,000 (1.3%)	197	260	1.3
Stevenage	75,000 (0.14%)	25	28	1.1

Table 4.3 Outdoor RLAN densities used in the simulations (systems per km^2)

Of these links, it is assumed (on the basis of data pertaining to currently operational systems) that there is a 50-50 split between omnidirectional and directional antennas, and that on average 10 % of the directional interferers contribute to the cumulative interference at the victim receiver. The above interferer densities should therefore be scaled by a factor of 0.55.

For modelling purposes we have assumed a uniform distribution of outdoor RLAN systems of

0.4, 0.8, and 1.6 per km^2, corresponding to low, medium and high penetration levels. As with indoor RLANs, FHSS / DSSS splits of 62% / 38% and 40% / 60% have been assumed.

4.3 Bluetooth

It is difficult to predict with any certainty the extent to which Bluetooth devices will penetrate the market, as the technology has yet to be launched. However, its' proponents firmly believe it will supersede cables and infra-red links to become the primary means of connecting PCs and peripherals. Ericsson recently announcing an integrated Bluetooth module for use in OEM equipment, forecast that up to 100 million Bluetooth devices may be in use globally by 2002. Meanwhile, National Semiconductor has released a single-chip radio transceiver (LMX3162), for applications such as Bluetooth or HomeRF, priced at under $6 in volume quantities. The Bluetooth SIG now has more than 800 members, suggesting ubiquitous acceptance among the IT and telecommunications communities.

We believe that a realistic long term assumption is that between 10% and 40% of mobile phone users will also be regular users of Bluetooth devices and that in busy hour periods these will be operational for 10% of time (this corresponds to the 100 millierlang voice traffic figure assumed for business RFA users). Assuming that all those employed in relevant sectors (section 4.2) are regular mobile phone users, this would imply that in a city like Glasgow with 400,000 employees the number of simultaneous Bluetooth transmissions in a busy hour period would be (assuming 20 % are regular users):

$$400{,}000 \times 20\% \times 10\% \quad = 8{,}000$$

$$\mathbf{= 40 / km^2}$$

For modelling purposes, to reflect the 10% to 40% usage range identified above, densities of 20, 40 and 80 Bluetooth transmitters per km^2 have been assumed, all transmitting at 1 mW EIRP, of which 80% are used indoors.

The emergence of Bluetooth as a ubiquitous, low cost RF connectivity technology has prompted speculation that its application could be far wider than the mere linking of PCs, mobile telephones and peripheral devices. Suppliers such as Ericsson have suggested that within a few years virtually every new mobile phone will incorporate a Bluetooth transceiver as standard. This raises the possibility that the technology could be used to enhance the capabilities or capacity of the cellular networks themselves, e.g. by the provision of indoor pico cells using Bluetooth repeaters, or enabling organisations to broadcast data locally to cellular handsets without having to use the networks' infrastructures. An example might be the transmission of departure times within the vicinity of airports or railway terminals.

Such developments could if sufficiently widespread have a significant effect on the interference environment at 2.4 GHz, particularly if a large proportion of transmission facilities were to be located outdoors. To consider this possibility , the effect of superimposing outdoor 100 mW Bluetooth transmitters at a density of 5 per km^2 onto a typical urban scenario has been considered.

4.4 Home RF

HomeRF is intended to bring many of the benefits currently enjoyed by business and commercial users of RLANs to small offices and homes. The effect in interference terms is therefore expected to be similar to that of RLANs in urban centres and modelling has been carried out in a similar fashion. The density of HomeRF systems is likely to be at its greatest in residential suburbs where there is a significant proportion of economically affluent and technologically aware potential users. An estimate of the likely density can be made to a first approximation by considering the population density of a typical suburban area such as Stevenage.

The population of Stevenage is 75,000. Assuming typical occupancy levels this corresponds to c. 19,000 dwellings. The likely take up is difficult to gauge but in the long term may be assumed to include a sizeable proportion of homes with more than one PC. According to research by Dataquest, up to 35% of homes in the US are likely to fall into this category by the year 2000. Assuming similar levels area achieved eventually in the UK, it is estimated that up to 30% of homes could in the long term make use of HomeRF connectivity.

In most cases, such systems are unlikely to be in use constantly but rather are likely to follow patterns similar to that of domestic telephones which typically operate at up to 7.5% of time[23] during the busiest hour of the day.

On this basis the density of HomeRF systems likely to be operational during the busiest time of day in a typical suburban area can be determined:

Density	=	(No. of dwellings x penetration x duty cycle) / land area
	=	(19000 x 0.3 x 0.075) / 25
	=	**17 / km^2**

This is similar to the "medium penetration" scenario for urban RLANs, except that in the HomeRF case all interferers are assumed to be using FHSS. A sensitivity analysis has been carried out by considering densities of 8, 17 and 34 systems / km^2. In each case, 80% of transmitters are assumed to be indoors and subject to a nominal 10 dB building penetration loss, the remainder outdoors.

4.5 RFID Systems

CEPT report SE(99)41, rev 6, includes market projections for various RFID devices in urban and rural scenarios. Projected unit densities range from a total of 8 per km2 to 430 per km2, depending upon the geographic area and assumed penetration. As these are substantially similar to the penetration levels we have projected for RLAN systems, and as the interference contribution from RFID devices is expected to be similar to or less than that from indoor RLANs (see section 2.4.1), the interference analyses involving indoor RLAN interferers are also considered to be valid for RFID interferers.

4.6 Other Systems

In all of the above scenarios, it is necessary to allow for the likely deployment of the other devices and applications referred to in section 2. The principal effect of many of the ISM

[23] This figure is consistent with the dimensioning of the Atlantic RFA network at 70 millierlangs per residential subscriber.

systems is an increase in the ambient noise level around the 2450 MHz centre frequency at which the devices operate. In some cases the effect may be to render a portion of the 2.4 GHz band unusable, however this can be overcome by avoiding those frequencies, as Atlantic have done in Scotland.

OBTV systems present a serious interference risk, albeit one which is present only rarely in any particular location. The relatively narrow band involved means FHSS systems should still be useable, however interference into DSSS systems may be sufficient to render these inoperable for the duration of the interference unless they can be retuned to another carrier frequency.

SRDs are unlikely to be a serious source of interference in relative terms because of the low duty cycles involved, but may themselves suffer interference if operated in noisy outdoor environments.

4.7 Summary of interference scenarios addressed by this investigation

The following Table 4.4 presents a summary of the scenarios considered in section 5 of this report.

Victim	Interferer	Senario ref	Location			Operation		Penetration		
			Rural	Suburban	Dense Urban	Indoor	Outdoor	Low	Med	High
RFA	RLANs	5.1	✓	✓	✓	✓	✓	✓	✓	✓
	RFA	5.2	✓	✓	✓		✓		✓	✓
	Bluetooth	5.3			✓	✓				✓
	HomeRF	5.4	✓	✓		✓	✓			✓
	Other significant	5.5	✓*	✓*	✓*	✓*	✓*	✓*	✓*	✓*
RLANs	RLANs	5.6			✓	✓				✓
	RFA	5.7					✓	✓	✓	✓
	Bluetooth	5.8			✓	✓				✓
	HomeRF	5.9								
	Other significant	5.10	✓*	✓*	✓*	✓*	✓*	✓*	✓*	✓*
Bluetooth	RLANs	5.11			✓	✓				✓
	RFA	5.12			✓		✓			✓
	Bluetooth	5.13								
	HomeRF	5.14								
	Other significant	5.15	✓*	✓*	✓*	✓*	✓*	✓*	✓*	✓*
HomeRF	RLANs	5.16		✓	✓	✓	✓			✓
	RFA	5.17		✓	✓		✓			✓
	Bluetooth	5.18			✓		✓			✓
	HomeRF	5.19								
	Other significant	5.20	✓*	✓*	✓*	✓*	✓*	✓*	✓*	✓*

*as appropriate (i.e. depends upon the nature of the interferer)

Table 4.4 Interference scenarios considered for modelling purposes

5 INITIAL INTERFERENCE ANALYSIS

In this section, the potential for inter-system interference is considered for each of the scenarios identified, on the basis of the minimum coupling loss anticipated for each scenario. In each case, the relevant parameters of the interferer and victim systems are summarised and a static calculation made of the likely worst case interference level from a single interferer. The more significant scenarios are modelled in greater detail in section 6.

5.1 RLANs into RFA

In this case, both the interferer and victim system may use either FHSS or DSSS. Typical characteristica are as follows:

Interferer:

Parameter	FHSS	DSSS
Total EIRP:	-10 dBW	-10 dBW
EIRP per MHz:	-10 dBW	-20 dBW
Duty cycle:	1.27% (on each specific hop frequency)	100%
Antenna type:	Omnidirectional[24]	Omnidirectional[19]

Table 5.1 RLAN interferer transmitter characteristics

Victim:

Parameter	FHSS RFA	DSSS RFA
Interference limit	-120 dBW	-108 dBW
Receiver bandwidth	1 MHz	22 MHz
Antenna (indoor)	Omni, 8 dBi gain	Omni, 8 dBi gain
Antenna (outdoor)	Directional, 18 dBi	Directional, 18 dBi

Table 5.2 RFA victim receiver characteristics

The worst case scenario is likely to be an outdoor RLAN or wireless bridge transmitter within line of sight of an RFA base station. Interference into a base station is more serious than interference into a subscriber station as the link margin is smaller and all traffic on the base station may be affected rather than just a single subscriber.

The following graph illustrates the interference power level at the RFA receiver in such a scenario, as a function of the separation between interferer and victim:

[24] Although some RLAN systems (notably wireless bridges deployed in outdoor locations) may use directional antennas, for worst case analysis it is appropriate to assume omnidirectional coverage.

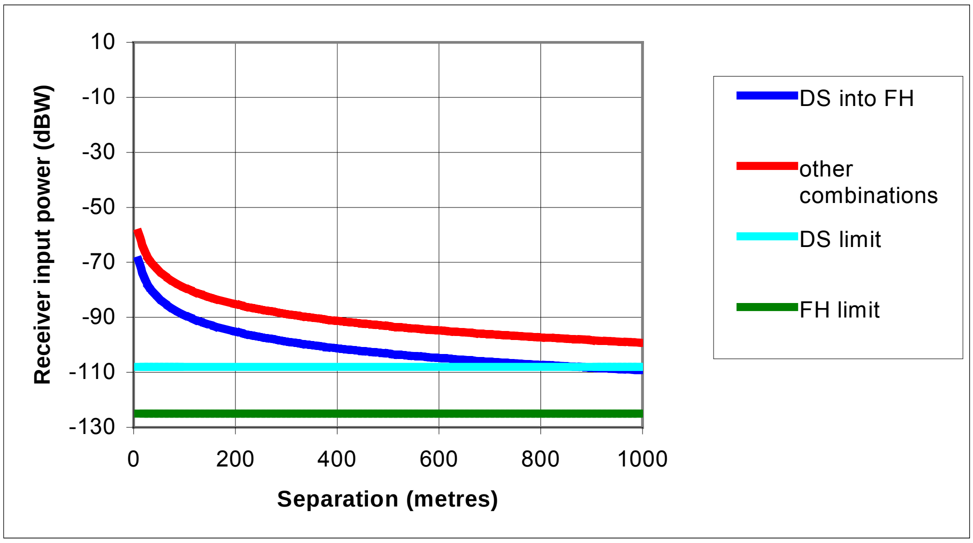

Figure 5.1 Interference power from RLAN transmitter into RFA receiver as a function of separation distance

It is clear that the interference limit will be exceeded whenever a line of sight path exists between interferer and victim. In the case of FH interferers, the result will be occasional collisions when the frequency of the interferer and victim coincide, and unless there are a large number of interferers the RFA system may be relatively unaffected. A DS interferer will be more problematic, even allowing for the lower power spectrum density, since the interference is present *continuously* within its 22 MHz wide RF channel. Up to 30% of the available hop frequencies in the 2.4 GHz band may thus be affected. It would in principle be feasible to configure the RFA system to avoid the affected frequencies (e.g. Atlantic currently use only 54 of the available 79 FHSS channels). This would not however counter the effect of multiple, co-located DSSS systems which may between them emit interference over the entire 2.4 GHz band, and would also make the victim more susceptible to other sources of interference such as ISM.

In practice, most *indoor* RLAN systems will be significantly shielded from the victim RFA antenna and individually will present little risk of interference. The cumulative effect of large numbers of systems within an RFA sector is modelled statistically in section 6 for the various scenarios defined in section 4. Outdoor systems, although fewer in number, are likely to be more problematic because coupling losses between interferer and victim are likely to be significantly lower.

Although DSSS victims can tolerate a higher instantaneous level of interference than FHSS victims, the probability of interference is much greater. Effectively, a single co-channel DSSS interferer would generate interference for 100% of the time, whereas a FHSS interferer would provide at least a 30% probability of interference within the victim receiver bandwidth. The probability of interference between two nearby FHSS systems is much lower, supporting the argument that FHSS systems have greater practical resilience against interference.

5.2 RFA into RFA

This scenario is similar to that involving an outdoor RLAN into an RFA system. Because each system need not use all the available hopping channels, there may be scope for co-ordination between operators (e.g. by assigning different channels to each operator), however this would reduce the ability of either operator to counter other interference sources such as RLANs or OBTV. Since an RFA operator must maintain an acceptable grade of service to its customers (typically 1% blocking or better) to remain viable, the implications of interference into an RFA network may be more serious than for a private system. Interference between two hypothetical RFA networks operatiing in the same geographic area is modelled statistically in section 6.2.2.

5.3 Bluetooth into RFA

Most Bluetooth devices are likely to differ from RLANs in two fundamental ways, namely:

- Lower EIRP (-30 dBW rather than –10 dBW)
- Shorter operational range (<10 metres rather than up to 1 km or more for outdoor RLANs).

Although the Bluetooth specifications include an option to increase power to –10 dBW, size and battery life considerations mean the emphasis is currently on the low power version. It can also be argued that applications requiring higher power are more akin to conventional RLAN systems rather than the “personal area network” concept that Bluetooth represents. For our initial interference analysis, it is therefore assumed therefore that all Bluetooth devices will operate at –30 dBW EIRP and will be used either indoors or at street level when outside.

These factors make line of sight interference paths unlikely, although where this does arise problems may occur. As the plot below shows, interference power from a Bluetooth transmitter along a line of sight path exceeds the threshold for a range of up to several hundred metres, even when the reduced 1 mW EIRP level is applied:

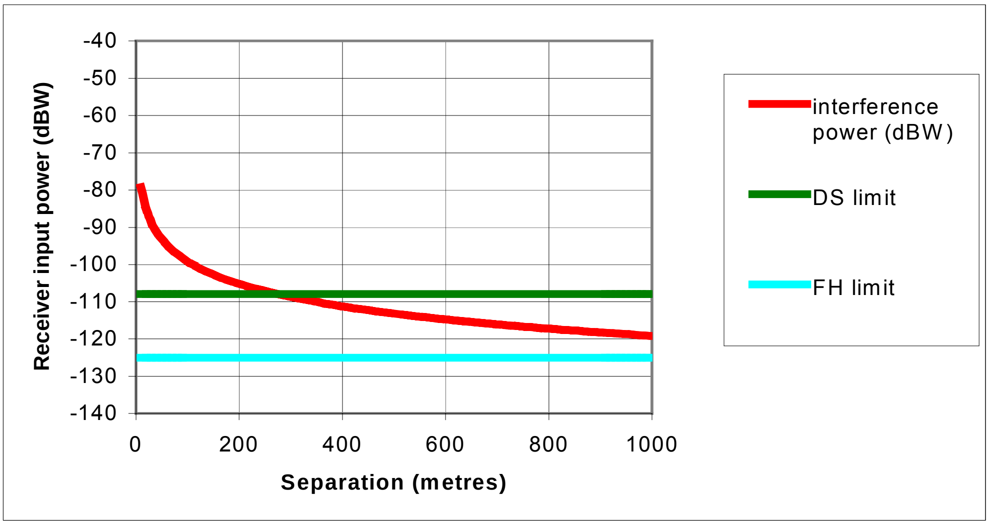

Figure 5.2 Interference power from a 1 mW Bluetooth transmitter into an RFA receiver, as a function of separation distance

In practice a bigger concern is likely to be the very high concentration of Bluetooth devices should the technology be as successful as some predict. This could lead to millions of the devices being deployed in the UK, albeit in most cases at relatively low duty cycles. This scenario is modelled statistically in section 6.2.3.

5.4 HomeRF into RFA

Whereas Bluetooth provides a relatively simple, low cost replacement for individual point to point cable links, HomeRF is intended to provide an integrated platform for networking all manner of electronic devices in the home, including PCs, printers, modems and digital cordless telephones (the SWAP standard is DECT compatible).

Under such a scenario, the worst case interference scenario for a single interferer and victim is likely to be comparable to that pertaining to RLANs, except that it is unlikely that directional outdoor antennas will be involved. Although the RF path between the home and outbuildings is clearly outdoor, it is assumed that the radio terminals will both be operated indoor and will employ relatively low gain (2 dBi) omnidirectional antennas, similar to cordless telephones.

Assuming a building penetration loss of 10 dB, the worst case interference level into an RFA receiver is likely to be:

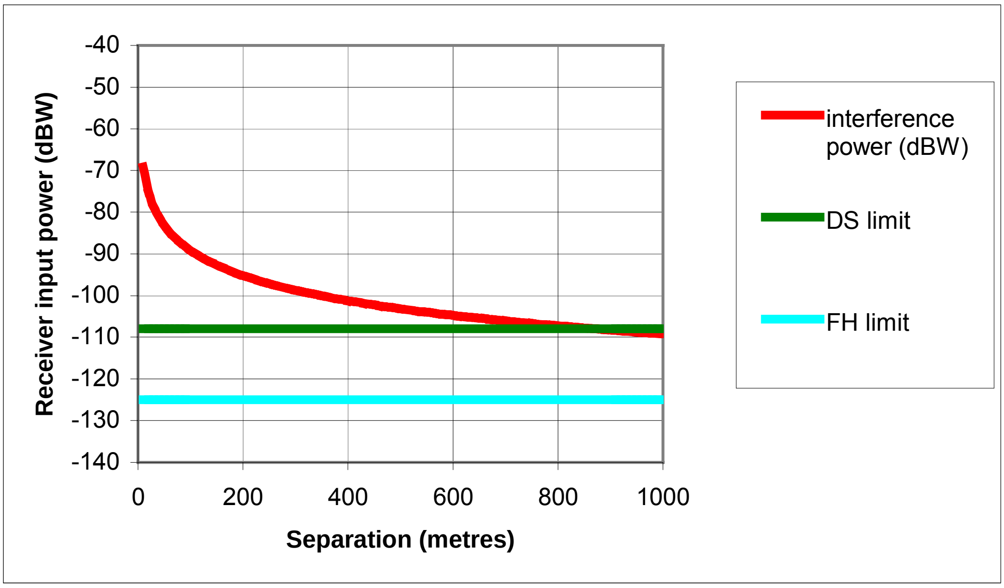

Figure 5.3 Interference power from HomeRF transmitter into RFA receiver as a function of separation distance

The cumulative effect of multiple HomeRF interferers, based on the penetration levels derived in section 4.5.4, is considered in Section 6.2.4.

5.5 Other significant interferers into RFA

5.5.1 OBTV

OBTV systems are potentially one of the most serious interference threats, merely by virtue of the very high powers involved. Conversely, their deployment is likely to be extremely rare at most locations and unless two or more systems are operating in the same areas the affected bandwidth should be sufficiently narrow to leave most FHSS channels unaffected. DSSS systems are likely to suffer greater outage if an OBTV system is transmitting within its RF bandwidth because interference will be continous for the duration of the OBTV transmission.

The introduction of digital links with narrower channel spacing but more uniform spectrum power density may make it more difficult for FHSS systems to avoid the affected frequencies but conversely the lower overall transmit power may reduce the effect on DSSS systems, although these are still likely to suffer more from in-band interference.

The worst case scenario is where a high power (40 dBW) temporary point to point links is deployed within sight of an RFA antenna. The plot below shows the interference level into an RFA base station in such a scenario. At very close range blocking may occur and that the whole band would be rendered unusable for the duration of the OBTV transmission. DSSS systems may be particularly prone to OBTV interference, since if the interference lies within the wanted signal channel it will be present continuously for the duration of the OBTV transmission. FHSS systems on the other hand will typically only suffer interference on channels close in frequency to the OBTV carrier.

Interference levels are significantly lower for hand held cameras and given the narrow bandwidth involved may not significantly affect FH systems unless operating at very close range. DS systems operating on a fixed carrier frequency may however be inoperable even if the interferer is at some distance, if the interference is within the wanted signal bandwidth and there is a line of sight path to the victim.

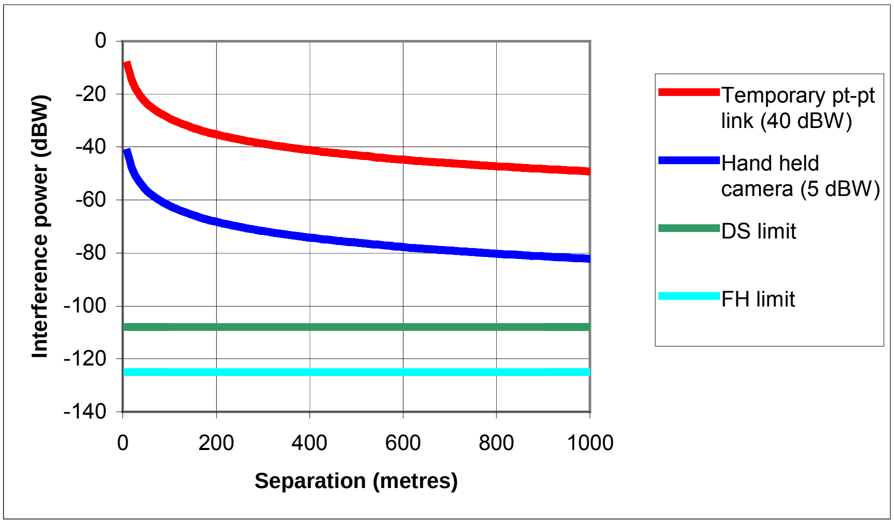

Figure 5.4 Interference from OBTV transmitters into RFA receiver as a function of separation distance

5.5.2 ISM Equipment

The biggest source of ISM interference in the band is from domestic microwave ovens. The market for these devices is a mature one and there is unlikely to be any significant increase in their number (any small increase in penetration is likely in any case to be offset by reduced leakage levels as newer models replace older ones). Monitoring by RA has shown that typical cumulative emission levels in a built up area of similar size to an RFA base station sector coverage area can be up to –90 dBW / MHz (section 2.4.1). Assuming a transmit spectrum mask corresponding to that in fig 5.1, the following interference power levels would be present at an RFA base station receiver:

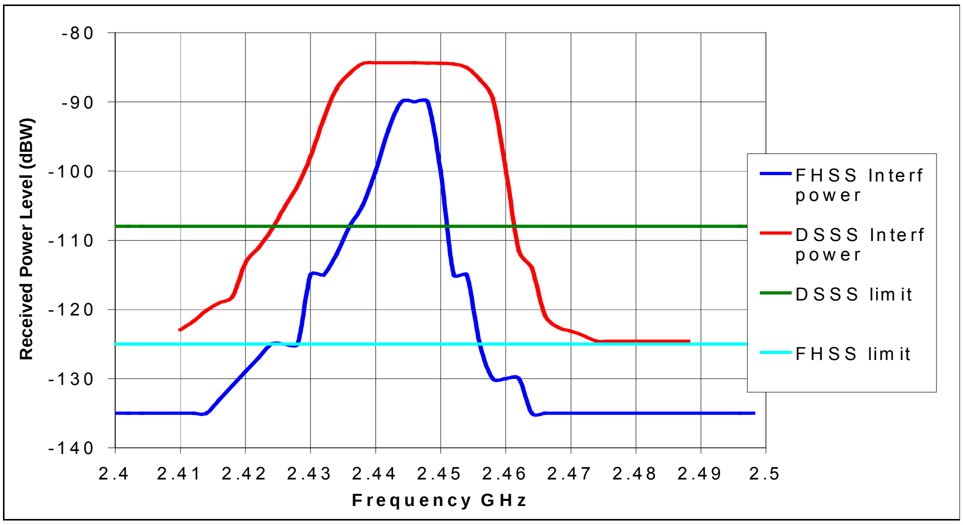

Figure 5.5 Interference from ISM systems into RFA receiver, based on RA laboratory tests on domestic microwave ovens

It can be seen that the RFA interference limit is exceeded over a 26 MHz bandwidth in the case of FHSS systems and 38 MHz for DSSS. Thus an FHSS system could minimise the effect of ISM interference by avoiding these channels (this is the approach taken by the Atlantic network in Glasgow which avoids the 24 most affected channels). It will be recalled from section 3.2.5 that the carrier frequencies available for DSSS operation under IEEE 802.11 are (in MHz):

2422	2427	2432	2437	2442	2447	2452	2457	2462

It can be seen that all except the highest and lowest channels would experience interference above the limit defined in section 3.2.5. Operation of a DSSS RFA system would therefore either be restricted to these two channels or need to deploy a greater link margin (i.e. higher minimum RSSI level) to overcome the additional interference indicated in the above graph.

5.6 RLANs into RLANs

IEEE 802.11 specifically provides for co-location of multiple RLANs by defining sets of orthogonal FHSS codes and providing for up to three non-overlapping DSSS channels in the 2.4 GHz band. Up to 15 FHSS RLANs can be co-located with minimal risk of collision and, according to equipment suppliers, up to 22 may be co-located before a significant reduction in data throughput is likely to be noticed. The cumulative effect of large numbers of indoor RLANs will be a slight increase in the noise floor, requiring a corresponding increase in the minimum RSSI level with a resulting reduction in operational range.

DSSS RLANs may in general only be co-located if they operate on different carrier frequencies. This is because of the requirement for a minimum S/N ratio in the spread bandwidth of 0 dB (BPSK) or 3 dB (QPSK), which rules out anything other than two equal power BPSK systems to be co-located on the same channel. Carrier frequency separation for co-located DSSS systems depends upon the degree of shielding between the systems. In the worst case scenario where there is no significant shielding it may only be possible to accommodate three co-located DSSS systems in the 2.4 GHz band.

It should be noted that, because all transmissions are at the full 100 mW EIRP level, typical link margins for RLAN systems are higher than for RFA systems where power received at the base station is equalised to within a few dB. Consequently, it is signals from the most distant station within an RLAN cell or subject to severe attenuation or multipath that are most likely to be affected by interference, either from other RLANs or from other transmissions in the 2.4 GHz band. In most cases where interference is experienced it should be possible to counter this by repositioning of affected terminals.

The cumulative wide area interference between indoor and outdoor RLANs is modelled in section 6.2.7.

5.7 RFA into RLANs

In this case, both the interferer and victim system may use either FHSS or DSSS, although as previously noted our expectation is that RFA systems are most likely to use FHSS. Key parameters are:

Interferer:

Parameter	FHSS	DSSS
Total EIRP:	-10 dBW	-10 dBW
PSD EIRP:	-10 dBW / MHz	-20 dBW/MHz
Duty cycle:	33.3% max (on each specific hop frequency)	100%
Antenna type:	60^{o} sector	60^{o} sector

Table 5.3 RFA interferer transmitter characteristics

Victim:

Parameter	FHSS (2 Mbit/s)	DSSS (11 Mbit/s)
Interference limit	-115 dBW*	-108 dBW
Receiver bandwidth	1 MHz	22 MHz
Antenna (indoor)	Omni, 8 dBi gain	Omni, 8 dBi gain
Antenna (outdoor)	Directional, 18 dBi	Directional, 18 dBi

*Based on CCA threshold for CA/CSMA protocol

Table 5.4 RLAN victim receiver characteristics

An outdoor victim with its antenna directly aligned with the interferer is the worst case by a significant margin, because of the relatively high antenna gain and the lack of any building penetration loss. Assuming a clear line of sight path between the two, the interference level at the victim receiver as a function of distance will be:

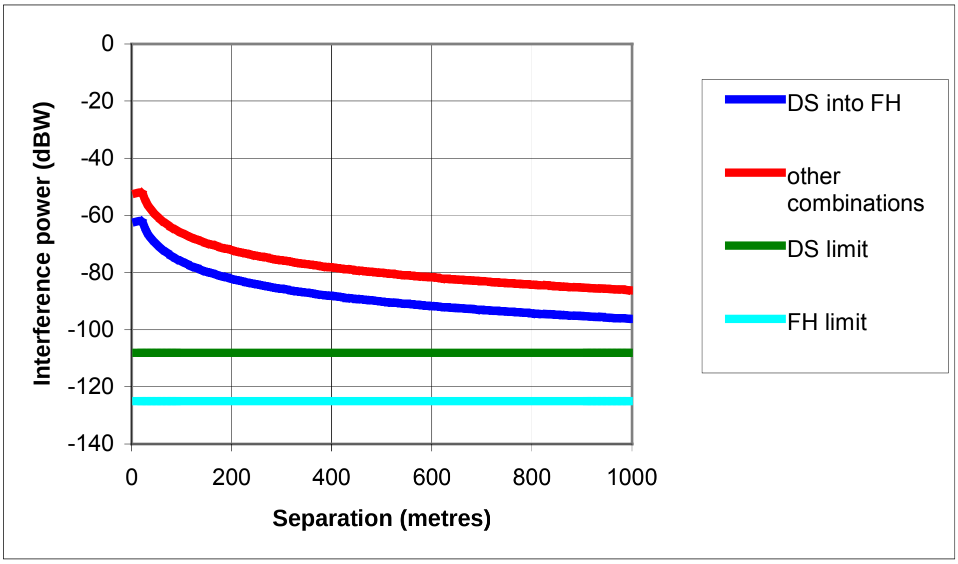

Figure 5.6 Interference from RFA transmitter into RLAN receiver as a function of separation distance

It can be seen that although DS systems can tolerate higher levels of total interference, this gain is offset by the wider bandwidth, which results in a higher probability of interference from nearby FH systems. Note however that in many cases operation may still be possible even when the above interference limits are exceeded. Interference between FH systems is not continuous but takes the form of occasional co-channel or adjacent channel collisions which result in a progressive slowing down in data throughput rather than complete system failure. Interference into outdoor systems can be countered by the use of directional antennas if the interferer is from a different direction from the wanted signal.

Where interference arises between two DS systems, the most effective solution is to ensure that the two systems operate on separate, non-overlapping radio channels. This option may not be available if all available channels are already in use at the affected location. In such a case, the only option is to increase the link margin of the affected parts of the victim system.

Section 6 considers the cumulative effect of various densities of RFA base stations on the various private systems in the band.

5.8 Bluetooth into RLANs

Many Bluetooth devices may be used alongside RLANs in indoor environments and this may lead to occasional frequency collisions. However the relative low power emitted by most Bluetooth devices means their effect at distances more than a few tens of metres from an RLAN receiver is likely to be insignificant. For example, a Bluetooth transmitter at a distance of 100 metres from an RLAN receiver will produce the following power at the RLAN receiver, assuming a clear line of sight path between the two:

P_{rx} = Ptx – FSPL + Grxant

= -30 – 100.6 + 2

= -128.6 dBW.

This is 8.6 dB below the interference limit for the RLAN receiver. Of course, a smaller separation between the interferer and victim or the use of a directional receive antenna on the RLAN will lead to higher levels, but in the case of the directional antenna with a correspondingly lower probability of a frequency collision.

5.9 HomeRF into RLANs

Since HomeRF is intended for deployment in the home and RLANs in business or commercial environments, the likelihood of there being significant interference between the two is small. The biggest risk is likely to be interference into outdoor RLAN receivers, particularly if there is a sizeable penetration of HomeRF systems in the longer term. The effect will be similar to that of HomeRF into RFA systems, except that the outdoor RLAN will typically have a higher link margin and hence be more resilient to interference.

Modelling results for this scenario are presented in section 6.2.10.

5.10 Other significant interferers into RLANs

The biggest potential interference source into RLANs is from domestic microwave ovens and other ISM equipment, where these are located close to RLAN terminals or access points. Suppliers of RLANs advise users to avoid locating terminals within 2 - 3 metres of such devices.

RLANs may also be affected by interference from OBTV systems, in particular DS RLANs may become inoperable if very high levels of narrow band interference are encountered within the RF bandwidth of the victim system. This is a particular risk for outdoor systems where , as in the case of an RFA victim, direct alignment between victim and interferer could result in very high levels of interference (see section 5.5.1).

It is interesting to note anecdotal evidence cited by one supplier of FH RLAN systems who supply FH vehicle telemetry systems to a Formula 1 racing team. The system normally operates in the 2.4 GHz band but must be modified to operate at 5 GHz at UK circuits because of interference which would otherwise result from on-site OBTV transmissions.

5.11 RLANs into Bluetooth

Interference into Bluetooth systems from indoor RLAN systems is likely to be a common occurrence, but given the very short range requirement it is unlikely that this will significantly affect the performance of Bluetooth links. It is possible that receiver blocking may occur if a Bluetooth device is placed immediately adjacent to an RLAN transmitter but this could be readily rectified by relocation of one or other of the terminals. The worst case scenario is likely to be interference from a DSSS RLAN, particularly if a number of these are co-located resulting in interference over the full 2.4 GHz band. Where such an interferer is located 10 metres from the Bluetooth victim, the interference will be:

-20 - 60 = **- 80 dBW / MHz**.

To maintain a 15 dB C/I level in this situation, the Bluetooth receiver would need to be at a maximum range of 2 metres. On this basis it seems likely that Bluetooth would experience difficulties operating within the vicinity of a high density DSSS RLAN system

5.12 RFA into Bluetooth

The use of low gain omnidirectional antennas on Bluetooth equipment and the relatively high link margins in normal use mean interference from RFA systems is unlikely to be an issue, particularly if, as seems likely, operators continue to favour FHSS technology.

5.13 Bluetooth into Bluetooth

As a low power, short range frequency hopping technology, Bluetooth seems to be ideally suited to high density operation. As noted elsewhere in this document, up to 22 frequency hopping systems can be typically co-located with similar receive power levels and it is unlikely there would be more than this number of Bluetooth devices located within the typical 10 metre operating range. The likelihood that many Bluetooth applications will comprise point to point links between devices, rather than the complex point to multipoint configurations typical of RLAN, implies relatively low duty cycles which will further reduce the probability of intra-system interference.

The potential use of 100 mW Bluetooth transmissions to provide wider area broadcast coverage, as noted in section 4.5.3 above, is unlikely to have a significant effect on interference into Bluetooth systems. This is because, unlike an elevated outdoor RFA or RLAN antenna, it is unlikely that more than one or two such transmitters would be visible to a typical Bluetooth receiver.

5.14 HomeRF into Bluetooth

This scenario is similar to 5.11 (RLANs into Bluetooth), except that all interferers will be FH and there is little likelihood of multiple co-located interferers. It is therefore considered that there is negligible risk of significant interference between these two systems.

5.15 Other Significant interferers into Bluetooth

The only situation in which it is envisaged that Bluetooth may encounter interference from other interference sources in the 2.4 GHz band is where a terminal is used directly adjacent to a domestic microwave oven, however this is unlikely to be a major constraint on its deployment. Other than extreme examples (such as the user of a hand held camera attempting to use a Bluetooth enabled device at the same time), OBTV is unlikely to have any significant effect on Bluetooth because of its narrow bandwidth.

5.16 RLANs into HomeRF

For interference evaluation, HomeRF may simply be considered as a FH RLAN. This scenario is therefore effectively addressed by 5.6, although in practice the probability of interference is likely to be lower still because it is unlikely that more than one or two HomeRF systems would be co-located.

One situation where interference may arise is where a HomeRF terminal is used out of doors (e.g. as a cordless telephone). Whilst FH interference is unlikely to be a problem because only occasional collisions would occur, high levels of DSSS interference could lead to reduced working range for the HomeRF device. For example, the presence of a DSSS RLAN transmitter at a distance of 100 metres could result in a worst case interference level of -100 dBW / MHz. Assuming the HomeRF base station to be indoors with a 10 dB building penetration loss, the working range of the HomeRF system could be reduced to c. 20 metres or less in this scenario.

5.17 RFA into HomeRF

This scenario is effectively addressed by 5.7 (FH victim). As with RLAN interference, where HomeRF terminals are used out of doors interference could arise, however this is unlikely to have a significant effect on the performance of the victim systems so long as the interferer uses FHSS. As noted in 5.16 above, the presence of an outdoor DSSS interferer may reduce the working range of a HomeRF system if terminals are used outdoors.

5.18 Bluetooth into HomeRF

As both of these systems use FHSS and are likelihood of multiple co-located systems in a home environment is small, the potential for interference between these two systems is considered negligible.

5.19 HomeRF into HomeRF

Use of FHSS allows typically up to 22 systems to be collocated. It is considered most unlikely that any scenario would arise in a domestic environment where this number of FH systems would be exceeded. The potential for interference between HomeRF systems is therefore considered to be negligible, other than a slight reduction in the maximum working range should very large user densities arise in the long term.

5.20 Other Significant interferers into HomeRF

As with other communication devices, the principal source of interference in the home will be the domestic microwave oven. However this is unlikely to require anything more than ensuring that receiver terminals are not located closer than 2 - 3 metres away from an operational oven.

6 INTERFERENCE MODELLING

6.1 Modelling Methodology

6.1.1 Introduction

The purpose of the modelling is to establish the likely level of interference into victim receivers where a statistically large number of interferers are present and the time, location and frequency of the interference is random in nature. For the cases considered in this study, the interfering sources will generally be fixed in location, but at any instant a different selection will be active. Furthermore, for the case of frequency hopping systems, even if all stations were continuously active and fixed, the distribution of interferers would appear to change as the hopping sequence progressed.

In principle, it would be straightforward to model the interference environment deterministically for a specific area, such as Stevenage or central London. In practice, however, data on the actual locations of the various interferers will be unobtainable, and conclusions would be hard to apply to other cases unless a wide range of models were constructed. For these reasons, a Monte Carlo modelling approach was adopted.

In the Monte Carlo model, the interferers and the environment in which they exist are characterised by statistical distributions. Thus, in the model used in this study, it was assumed that interferers of different types are scattered uniformly (to a specified density) over a given area. Each potential interferer is then determined to be active or not according to a Poisson distribution. The antenna height above ground for each individual interferer may be drawn from either a rectangular or a Gaussian distribution, and building loss is assumed to follow a Gaussian (in dB) distribution.

The interference simulation and modelling tool is an Aegis in-house written application which utilises a range of input parameters and calculates the aggregate interference from a maximum of three different interfering systems into a victim system at a particular operating frequency.

6.1.2 Probabilistic nature of interference to / from FHSS systems

For FHSS systems, account must be taken of the probabilistic nature of interference on any single hop frequency at any given time. In the detailed modelling which is reported in section 5, this is done by scaling the distribution of FHSS interferers by a factor equivalent to the number of hopping channels (78 have been assumed in the case of RLANs, 54 in the case of RFA). The model then determines the probability of a given level of interference being exceeded for a given percentage of time, from which the number of affected hopping channels at any instant in time can be determined.

Where frequency hopping interferers are involved, the density of interferers used in the modelling is further reduced by a factor equal to the number of hopping channels, to represent the number of FHSS interferers transmitting on a specific channel at any given time. It is assumed that there is an equal probability of any available channel being active at any given time for a FHSS system.

For interference into FHSS systems, we have assumed that up to 10% of available hopping channels may be affected by interference at any one time. Discussion with equipment suppliers and users have indicated that this is likely to enable an acceptable level of system performance to be maintained.

Interference from DSSS systems and ISM systems will be assumed to be present at all times. Interference from OBTV systems is assumed to occur on rare occasions but continuous when it does occur.

6.1.3 Propagation Considerations

Because of the variety of systems that may be deployed in the 2.4 GHz band, it is necessary to consider a number of propagation scenarios. It has already been noted that RFA networks typically assume a clear line of sight between transmit and receive stations and that a free space model can therefore be applied. However, even in this case monitoring shows that actual received power levels can be 10 dB or more below that which would be expected. This may be due to such factors as knife edge diffraction or imperfect antenna alignment.

Base stations must be elevated sufficiently to provide line of sight visibility of a reasonable number of potential subscribers. Typically this requires an elevation of 50 –100 metres, though this might be less in suburban or rural locations. Subscriber antenna height is constrained by the height of the subscriber premises, typically of the order of 5 – 10 metres.

Outdoor RLAN systems are likely to use similar elevation levels, except that “subscriber” antennas (e.g. those used to deliver Internet services to school buildings) will be somewhat higher (15 – 30 metres typical).

Most RLAN systems are likely to be deployed indoors and will to some extent be shielded from other 2.4 GHz transmissions. The siting of user terminals and Access Points is critical in this regard and care should be taken to avoid siting access points in locations prone to interference (e.g. beside windows or close to internal interference sources such as microwave ovens.

In this study a variety of models have been used to represent outdoor propagation. Free-space propagation (an R^2 law) will obviously give a worst-case result, useful for bounding purposes. An empirical model has also been used, namely the well-known Okumura-Hata method (with the mobile height correction for 'medium' urban areas). This empirical model is intended to represent the case of an elevated base station operating with mobile terminals and is considered appropriate for the modelling of interference involving indoor RLANs, Bluetooth and HomeRF devices. For outdoor RLANs a further, simple, model was introduced in which path loss was assumed to be free-space to a distance of 1 km, and to follow a R^4 law thereafter - this is referred to as the 'multislope' model. A similar model has been used by Atlantic Telecom in connection with its own network planning.

Interference from indoor systems is modelled by the association of a 'building entry loss' value with each indoor source. This value is assumed to be Gaussian distributed, with a mean value of 10 dB and a standard deviation of 3 dB[25].

6.1.4 Modelling Software

The interference simulation and modelling tool is an in-house written application which utilises a range of input parameters and calculates the aggregate interference from a maximum of three different interfering systems into a victim system at a particular operating frequency.

6.1.4.1 Input parameters

The input parameters are divided into three groups. First group is the set of general parameters. These are:

- operating frequency (in MHz) of both victim and interferer(s)
- exclusion distance (in km) around the victim system in which the occurrence of interfering systems will not be considered
- maximum distance (in km) away from the victim. At distances larger than the maximum distance, simulation will not be performed and any occurrence of potential interference in that area will not be considered.
- number of interference calculation trials

The second group considers input parameters relating only to potential interferers. These parameters are :

- number of interfering system types
- average interfering system antenna height (in metres)
- interferer antenna height distribution (Rectangular or Gaussian)
- interferer antenna height standard deviation (in metres)
- average building penetration loss (in dB)
- building penetration loss standard deviation (in dB)
- interferer EIRP (in dBW)
- density of interferers (in sites per square km)
- interferer activity distribution (Poisson or Uniform)

All of the above parameters need to be specified for every interfering system type. Finally, the third group of input parameters is related to the victim system. The input parameters in this group are:

- victim antenna height (in metres)
- victim antenna downtilt (in degrees)
- victim antenna gain (in dBi)

[25] These figures are intended only to be plausible, and do not relate to any specific empirical data.

- victim antenna pattern (sectorised or user specified or antenna pattern based ITU Recommendation F.669)

6.1.4.2 Model Operation

The tool calculates the aggregate interference from all specified interfering systems for a large number of iterations (typically 1000 or more). A number of different propagation models can be used for interference calculation. For this study we have chosen the Okumura-Hata urban model and a R^2 / R^4dual slope model with a break point at 1 km (see 6.1.3 above). Once the interference calculations are complete, the tool generates a probability density function (PDF) and cumulative density function (CDF) for interference levels in 1 dBW steps. The CDFs are then plotted against the interference levels.

6.1.5 Modelling input assumptions

DSSS interferers are modelled on the basis of a random distribution of continuous emissions, each occupying nominally one third of the available bandwidth in the 2.4 GHz band (this reflects the practical limit of three non-overlapping channels). From this is derived the probability of interference on any given 1 MHz channel at a typical location appropriate to the scenario being modelled. The power spectral density is assumed to be -20 dBW/ MHz, consistent with the limit defined in ETS 300 328. Note that, unlike FH interferers, a DS interferer emits continuously on its radio channel and therefore if a DS interferer is sufficiently close to a victim receiver to exceed on its own the receiver's interference threshold, the victim will suffer interference at all times on the affected channels, i.e. at least 22 contiguous 1 MHz channels are likely to be affected in the case of a FHSS victim. The statistical modelling therefore provides an indication of the number of channels likely to be affected at a *typical* site; the number of channels affected at individual sites may be higher or lower depending in particular upon whether one or more DSSS interferers are located nearby.

In most cases the split between FHSS and DSSS systems has been assumed to be 68% and 32% respectively[26]. An indication of the relative effect of DSSS and FHSS interferers in a wide area scenario is however provided by modelling certain scenarios with DSSS as the dominant technology, using a split of 40% FHSS, 60% DSSS[27].

Note that the modelling results relating to interference into indoor RLANs also provide an indications of the likely interference levels into Bluetooth and HomeRF devices, which have similar antenna and receiver characteristics.

6.1.6 Interpretation of results

A typical simulation will consist a large number of successive trials, to ensure that the interferer distributions are adequately sampled, and the result is given in the form of a probability distribution of interference power at the victim receiver. It is necessary to interpret this distribution with some care: it is tempting to regard the probability axis as relating to time, but this is not strictly the case. The probability really relates to the likelihood of a victim

[26] Based on Frost and Sullivan Study

[27] Arbitrary choice for comparative purposes.

receiver experiencing a given level of interference if randomly located in an area characterised by the distributions discussed above. Thus, if a model was run with input distributions judged representative of, say, Stevenage in the year 2003, and the interference limit was found to be exceeded with 33% probability, the inference would be such that if a large number of receivers were randomly located in that area at around that date, around a third of them would suffer interference beyond the limit. It would not be the case that a given receiver would experience interference for 33% of the time (except in the case of interference from a FHSS source, for the reasons explained in 6.1.2 above).

In the case of FH victim receiver, the output distributions translates into an estimate of the number of hopping channels which are likely to be affected by interference at any time, which in turn enables a qualitative assessment of the effect upon system performance to be made. For DSSS victims, it is assumed that the effect of a FHSS interferer which lies with the 22 MHz bandwidth of the wanted DSSS signal is the same as a continuous 1 MHz wide interferer at the same power level an on the same carrier frequency as the DSSS wanted signal.

6.2 Modelling Results

6.2.1 RLANs into RFA

A number of simulations have been carried out for this combination, reflecting the various penetration scenarios proposed in section 4.5.2.

Initially, each of the following interferers was modelled individually:

i. Indoor RLANs with 68% FHSS, 32% DSSS at the following geographic densities (systems per km^2): 1, 2.5, 5, 10, 20, 40, 200, 400 and 800.

ii. Indoor RLANs with 40% FHSS, 60% DSSS at the following geographic densities (systems per km^2): 5, 20 and 400 per sq km

iii. Outdoor RLANs with 68% FHSS, 32% DSSS at the following geographic densities (systems per km^2): 0.75, 1.5 and 3

6.2.1.1 Indoor RLANs

Plots were generated of the interference cumulative distribution function (CDF) for each of the geographic densities listed in 6.2.1 (i) above. The CDF shows the probability over time of interference exceeding a given level which, for a frequency hopping interferer, corresponds to the proportion of hopping channels likely to experience interference at or above that level at any given time. The following plot shows interference CDFs for indoor RLAN density of 10, 20, 40 and 800 per km^{2,}, representing low medium and high penetration in a typical urban area and an absolute worst case based on the City of London:

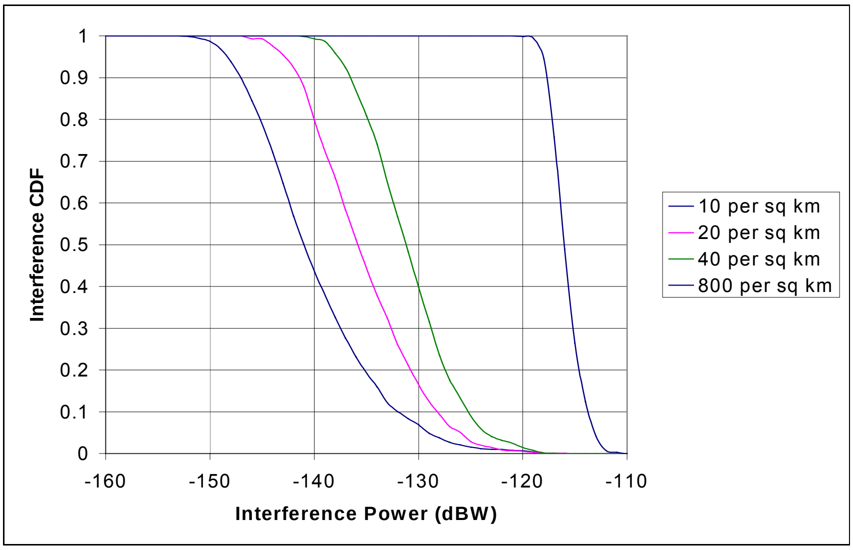

Figure 6.1 Interference CDF for Indoor RLAN transmitters into RFA receiver

The plot indicates that, for example, in the 10 interferers per km^2 scenario, 10% of hopping channels are likely to have interference at or above -133 dBW, 20% are likely to have interference at or above -138 dBW, and so on. By comparing the results for each simulation, it is possible to determine the density of indoor RLAN interferers at which a given proportion of hopping channels are likely to suffer interference above the acceptable threshold for RFA network operation. On the basis of discussion with FHSS equipment suppliers and users, it has been assumed that for satisfactory network operation, at least 90% of the available hopping channels must have interference below the -95 dBW limit defined in section 3.1.3.

The following plot shows the predicted interference for 10% of time vs the density of indoor RLAN systems, derived from CDF plots such as the one above. Again, a nominal 10 dB building penetration loss is assumed and the propagation model is Okumura - Hata. Two plots are shown, corresponding to the two different splits between DSSS and FHSS RLANs defined in 4.5.2 above.

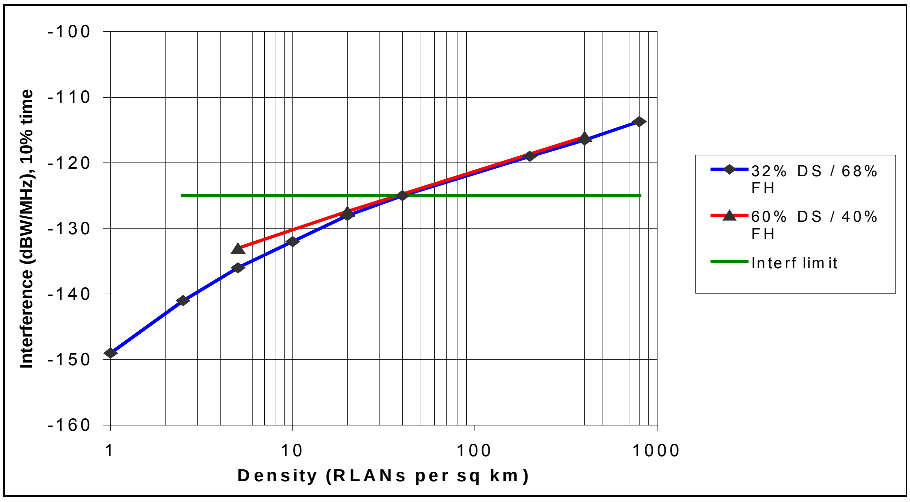

Figure 6.2 Interference level (10% CDF) for indoor RLAN transmitters into RFA

receiver as a function of indoor RLAN density

The plot shows that the -125 dBW threshold corresponds to an indoor RLAN penetration level of 40 per km^2. At the anticipated worst case penetration level of 800 per km^2, the RFA operator would need to increase its link margin by c. 12 dB to overcome interference from indoor RLANs alone.

Note that at higher penetration levels the split between DSSS and FHSS systems appears to make little difference to the probability of interference.

6.2.1.2 Outdoor RLANs

The following plot shows the interference CDF corresponding to a typical urban density of 1.5 outdoor RLANs per km^2, using three different propagation models. The Okumura - Hata model, as used above for the indoor RLAN simulation, almost certainly overestimates the degree of clutter loss for outdoor systems, which will typically have elevated rooftop antennas. Conversely, the free space model is unduly pessimistic as it assumes even distant interferers have a line of sight path to the victim, most unlikely in practice. A third model has therefore been chosen, namely the "dual slope" model. This assumes free space path loss for distances up to 1 km, and an R^4 proportionality beyond. As would be expected, the CDF curve lies between the free space and Okumura models. The following plot shows the CDF curve for a typical urban density of 0.8 outdoor RLANs per km^2, using each of these three propagation models:

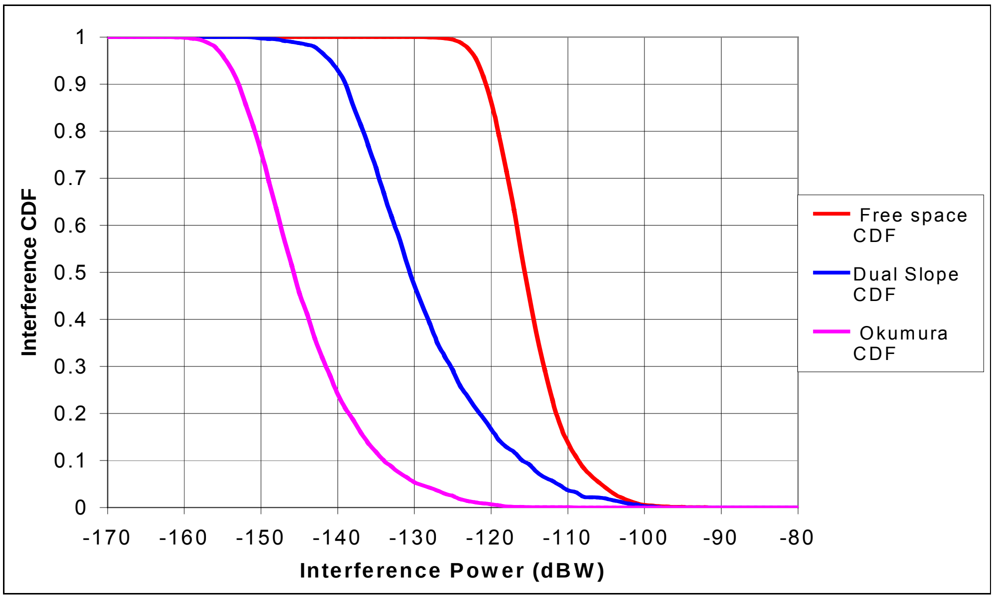

Figure 6.3 Interference CDF for Outoor LAN transmitters into RFA receiver

It can be seen that if the dual slope propagation model is assumed, 30 % of the hopping channels will suffer interference above the threshold. A 9 dB increase in link margin will be required to ensure that 90% of the channels have adequate protection from interference.

The plot below shows the cumulative level of interference vs the density of outdoor RLANs, for the two different splits between DS and FH systems.

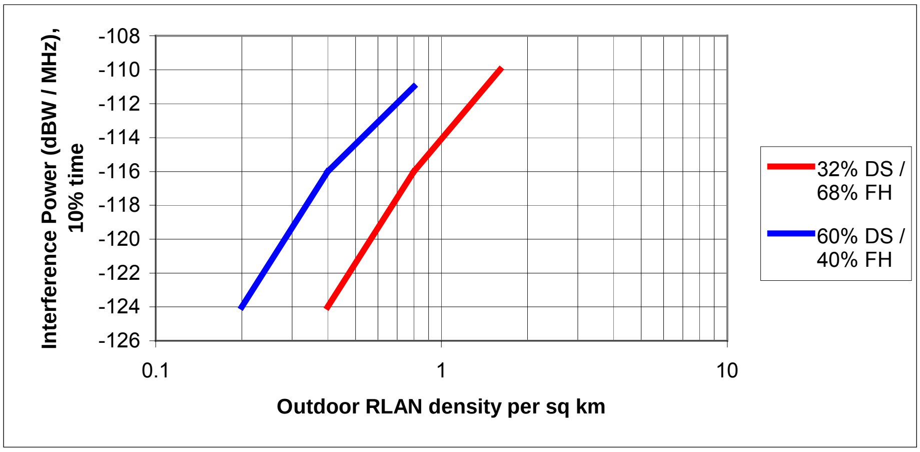

Figure 6.4 Interference level (10% CDF) for outdoor RLANs into RFA receiver as a function of outdoor RLAN density

The results show that, assuming that 68% of outdoor RLANs use FHSS, the 10% threshold is reached at a density of just under 0.4 systems per km^2. This is towards the lower end of the range of penetration levels that have been assumed in this study and implies that outdoor RLAN systems could cause interference into RFA systems planned on the basis of the current Atlantic network.

It can be seen that the form of the probability distribution depends on the ratio of DS to FH systems. The higher probability events reflect cases where interference is due to a very large number of interference entries from relatively distant sources via the receive antenna sidelobes. For the input parameters assumed in the modelling, the greater power of the FH systems is almost exactly balanced by the greater number of DS systems falling within an instantaneous receiver channel. Therefore, where large populations are considered there will be little difference between the two cases.

The low probability events correspond to the situation where the aggregate interference is dominated by one or two local interferers within the receiver main beam. As the FH systems have a greater power than the DS systems, it is obvious that the interference power in this case will be the greater.

6.2.2 RFA into RFA

A simulation has been carried out of two unco-ordinated, co-located RFA systems, each with characteristics based upon the Atlantic network.

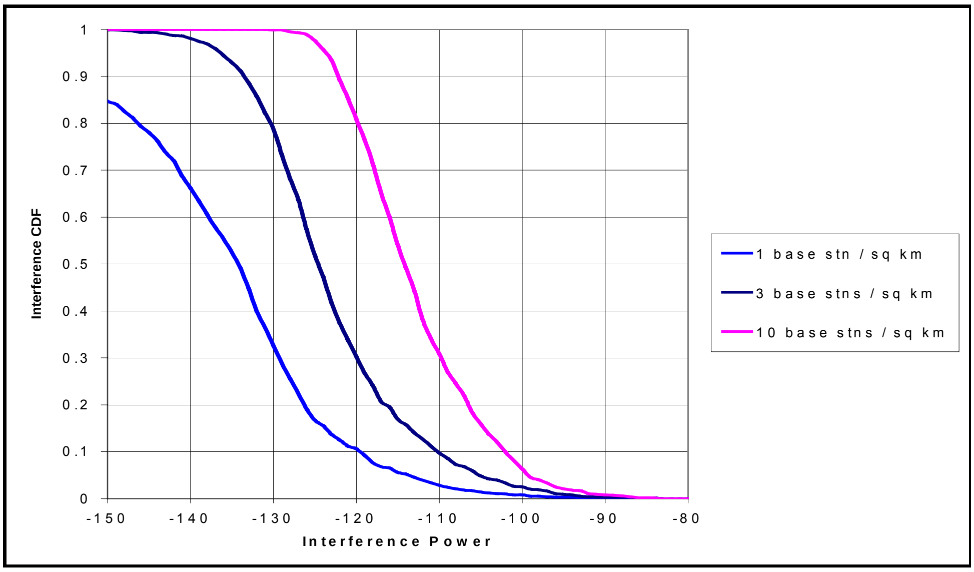

Figure 6.5 Interference CDF for two co-located FHSS RFA networks

From the plot it is clear that even at the lowest base station density, corresponding to today's relatively modest traffic levels, the -125 dBW interference threshold will be exceeded for over 15% of the time. At a density of 10 base stations per km^2 the threshold is exceeded almost continously. It is therefore considered most unlikely that two unco-ordinated RFA systems could co-exist in the same geographic area and maintain a reasonable grade of service to customers.

As noted in section 5.2, frequency partitioning could be used to accommodate two networks, however this would significantly reduce the ability of the networks to counter frequency selective interference from ISM or OBTV equipment. The geographic co-location of two or more RFA networks is therefore not recommended.

6.2.3 Bluetooth into RFA

Two distinct scenarios have been considered for this combination, namely a widespread proliferation of low power integrated devices and the possible use of Bluetooth for local area data broadcasts or cellular capacity enhancement. In the first scenario, densities of 20, 40 and 80 low power (1 mW) devices per km^2 (as derived in 4.5.3) have been used, 80% of which are assumed to be indoors and subject to a nominal 10 dB building penetration loss.

For the second scenario, a density of 5 high power (100 mW) outdoor Bluetooth transmitters per km^2 has been assumed. An Okumura-Hata propagation model has been used in both cases.

The following plot shows the Interference CDF for low power Bluetooth interferer densities of 20, 40 and 80 per km^2:

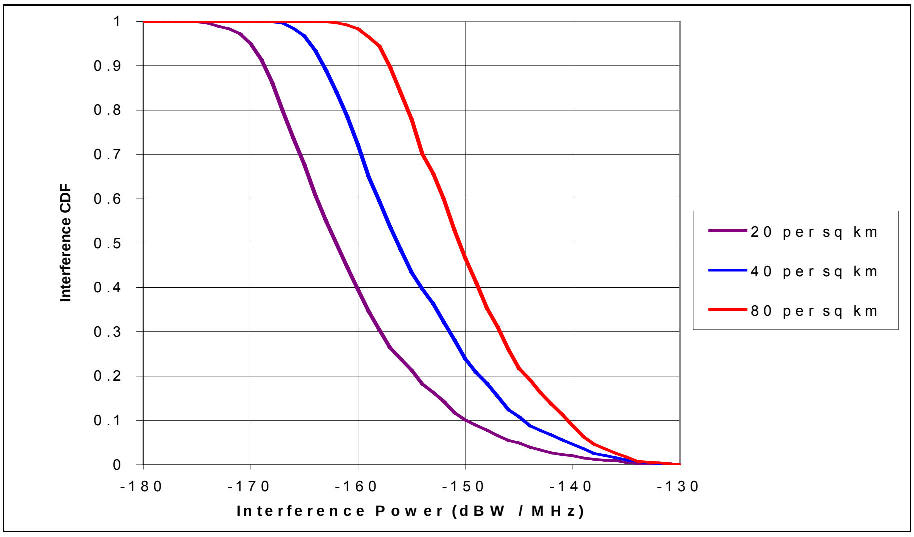

Figure 6.6 Interference CDF for Bluetooth transmitters into RFA receiver

It can be seen that interference levels are significantly lower than those for RLAN interferers, due principally to the lower power levels involved. It seems unlikely that Bluetooth will have a significant effect on total interference levels in the 2.4 GHz band, unless there is a widespread migration towards higher power (100 mW) transmitters, in which case interference levels would approach those for indoor RLAN devices. It is more likely that high power transmissions will be limited to applications similar to those currently served by RLANs, with the majority of applications such as cordless hands free kits and palmtop / phone interconnection continuing to use the more appropriate low power version.

6.2.4 HomeRF into RFA

This scenario has been modelled using the penetration levels derived in section 4.5.4, namely 8, 17 and 34 systems per km^2. 80% of systems are assumed to be indoors (subject to 10 dB nominal building penetration loss), and 20% outdoors. The Okumura - Hata propagation model has been used. The interference CDFs for each of the three penetration levels are presented below:

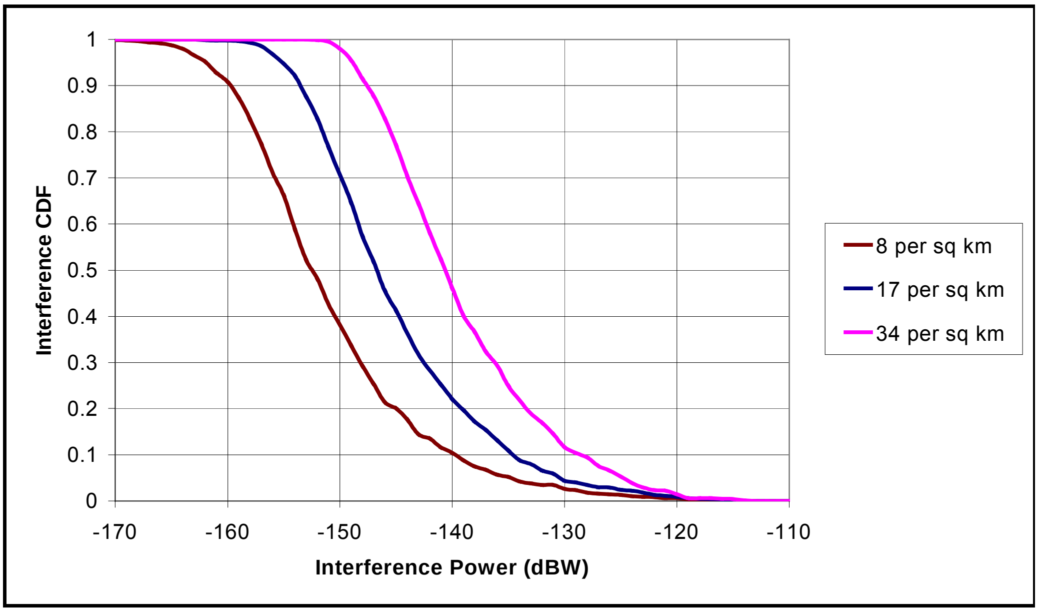

Figure 6.7 Interference CDF for HomeRF transmitters into RFA receiver

6.2.5 Other significant interferers into RFA

The effect of OBTV and ISM interferers has been modelled by adding a fixed level of interference on specific channels corresponding to the likely levels of interference. OBTV interference is based on the levels derived in section 5.5.1, assuming a separation between interferer and victim of 500 metres. Taking account of the analogue OBTV spectrum mask in section 2.2.1 and assuming a line of sight path, the interference mask into an RFA base station would be:

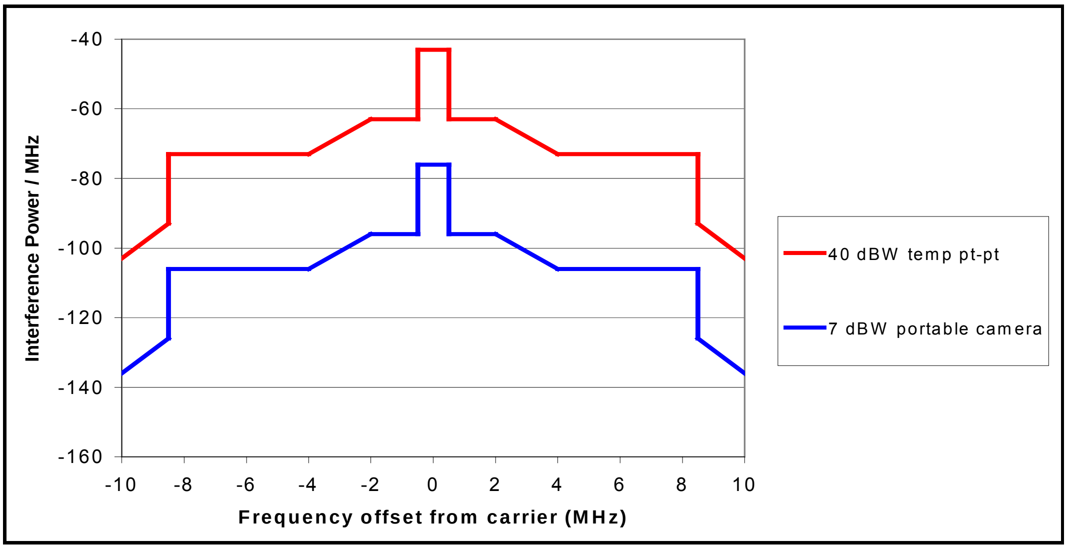

Figure 6.8 OBTV interference into an RFA base station receiver at a separation distance of 500 metres

It can be seen that the temporary point to point link produces interference above the -125 dBW threshold throughout its 20 MHz bandwidth, while the portable camera affects a 16 MHz band. It should be emphasised that the probability of a direct line of sight hit from a temporary point to point link is extremely low, given the highly directional transmit antennas involved and the declining use of these systems at 2.4 GHz in many areas. The portable camera with its omnidirectional antenna presents a more credible scenario but will still be a relatively rare occurrence and limited in general to specific sites such as racecourses or other venues where regular OBTV transmissions occur. It should therefore be possible to configure an RFA network to minimise the effect of such transmissions, either by avoiding popular OBTV sites or providing enhanced link margins in their vicinity.

ISM interference into FH and DS RFA receivers, based on typical urban levels at the worst time of day are shown in section 5.5.2.

6.2.6 Cumulative interference into an RFA network

The plot below shows the projected cumulative interference level into an RFA base station with an 11 dBi gain, 60^{o} sector antenna for the assumed worst case scenario, taking account of all the above sources. The scenario assumes the following interferer densities, consistent with the worst case scenarios derived in section 4.5, namely:

Interferer type	Penetration (per km^2)
Indoor RLANs and RFID devices	800
Outdoor RLANs	1.6
Low Power Bluetooth	80
High Power Bluetooth	5
HomeRF	34

Table 6.1 Interferer densities (systems per km2) assumed for probable worst case interference scenario

The assumed OBTV interferer is a portable camera operating at 2420 MHz, at a distance of 500 metres from the victim receiver. Interference levels from spread spectrum interferers are those corresponding to 10 % CDF.

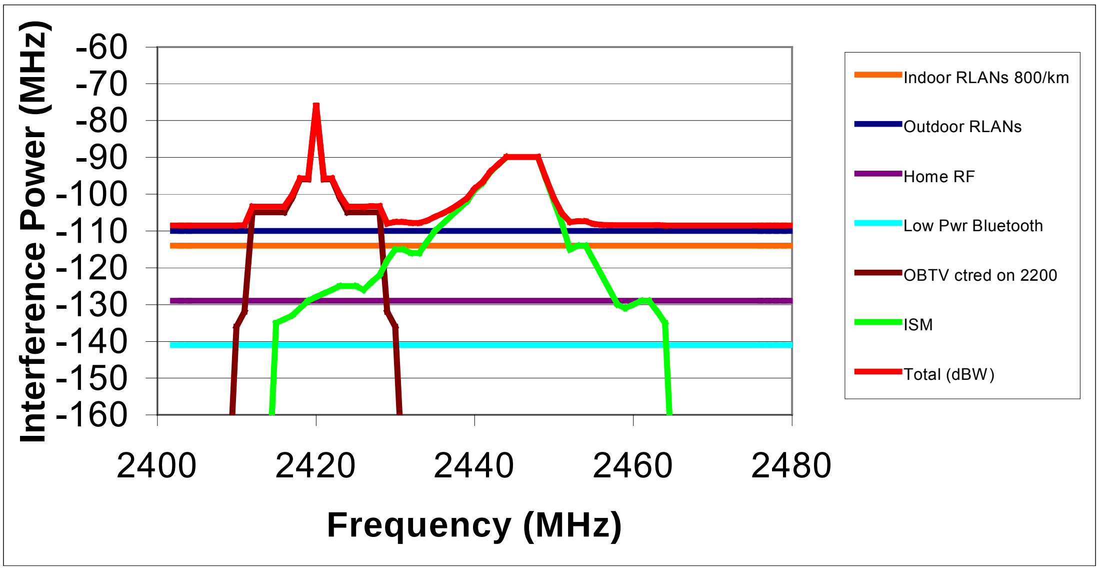

Figure 6.9 Interference contributions from various interferer types under probable worst case scenario

It is clear that even in this probable worst case scenario the cumulative interference over much of the band is dominated by ISM and OBTV interference, It has already been noted that an RFA operator may avoid ISM interference by judicious choice of frequency channels and that OBTV interference is a relatively rare, sporadic occurrence. It is therefore appropriate to concentrate on the interference levels generated by the spread spectrum communication systems in the band.

Even in the dense urban scenario to which the above figure relates, where indoor RLAN systems outnumber outdoor systems by over 500:1, outdoor systems still produce a greater level of interference. At the more probable typical urban penetration levels expected to arise outside the City of London, the dominance of outdoor systems is even more pronounced. The following table shows the interference level generated for 10% of the time for each of the principal spread spectrum interferer types, for low medium and high projected penetration levels:

Interferer type	Low Urban	Medium Urban	High Urban
Indoor RLANs	-132	-128	-125
Outdoor RLANs	-124	-116	-110
Low Power Bluetooth	-150	-145	-140
High Power Bluetooth			-131
HomeRF	-140	-134	-129
RFID	-132	-128	-125
TOTAL	**-122.7**	**-115.4**	**-109.6**

Table 6.2 Interference contributions from spread spectrum interferersinto RFA victim receiver, under typical urban penetration scenarios

It can be seen that outdoor RLAN systems dominate, particularly at higher penetration levels and are the only type of interferer individually to exceed the -125 dBW limit for the RFA receiver.

6.2.7 RLANs into RLANs

The effect of wide area interference between large densities of indoor and outdoor RLAN systems has been modelled. Interferer densities of 40 and 800 indoor systems / km2 and 1.6 outdoor systems / km2 have been considered into typical indoor and outdoor victim receivers. This is considered to be representative of the likely worst case urban and dense urban scenarios. The victims are assumed to have omnidirectional antennas (2 dBi in the indoor case, 10 dBi in the outdoor case) and building penetration loss is assumed to be a nominal 10 dB.

The following plot shows the CDF for interference from indoor and outdoor RLANs into a typical indoor RLAN system, assuming the worst case dense urban scenario of 800 indoor systems per km2 and the worst case urban outdoor RLAN scenario of 1.6 per km2:

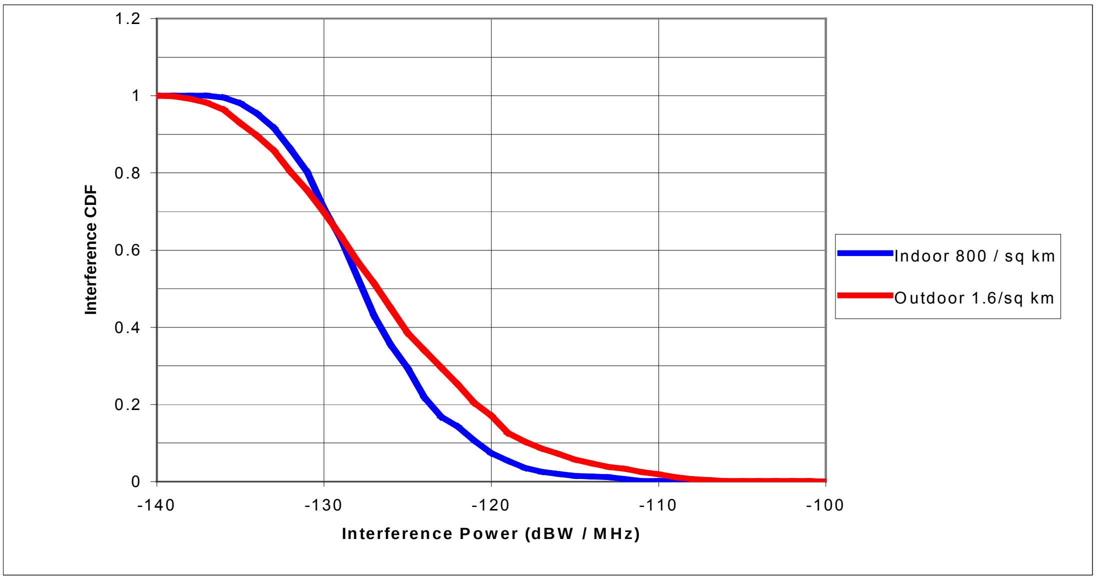

Figure 6.10 Interference CDF for RLANs into indoor RLAN reciever

It can be seen that despite the much greater density of indoor systems, there is still a greater interference contribution from the outdoor systems. In both cases, the interference present for 10% of time is slightly above the limit for noise limited operation, however with typical RLAN link margins there is unlikely to be a significant problem with intra-system interference even at these very high penetration levels.

Interference between outdoor RLANs is much more significant. The following plot shows the interference into a typical outdoor RLAN receiver with a 10 dBi gain omnidirectional antenna from other similar outdoor RLANs at a geographic density of 1.6 per km2 (high urban penetration scenario):

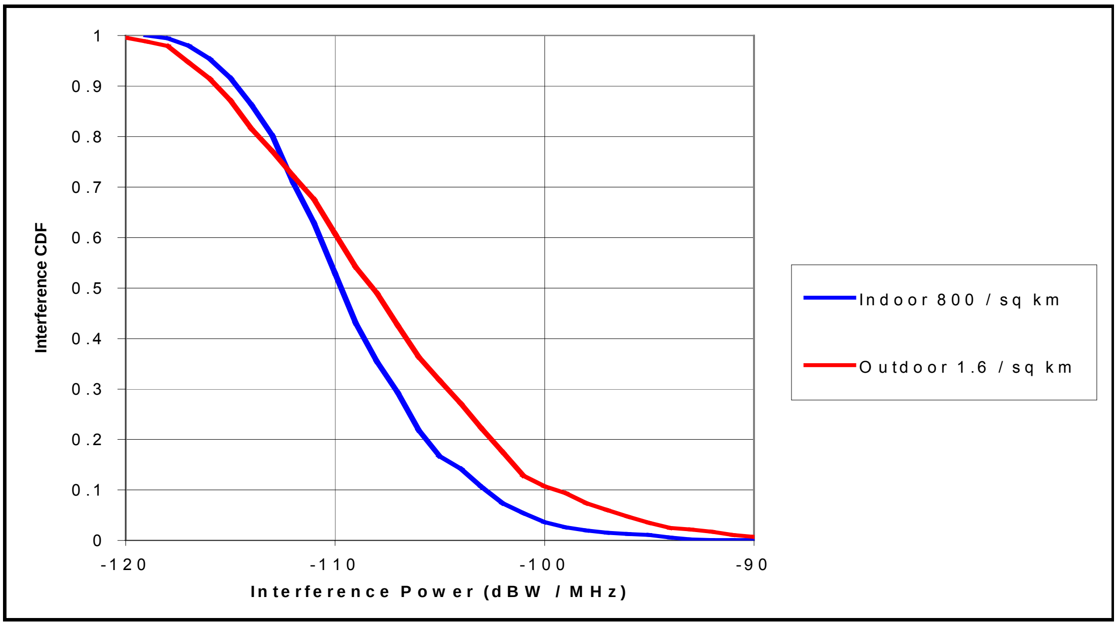

Figure 6.11 Interference CDF for RLANs into outdoor RLAN reciever

It is clear from this result that the density of outdoor RLANs will be largely self-limiting, in that the maximum working range will be considerably reduced at high link densities. For example, a wireless bridge spanning 1 km with 10 dBi gain antennas at either end will deliver -92 dBW to the receiver. To maintain error free transmission on individual hops in a FHSS systems, a 15 dB C/I ratio is required, hence interference should not exceed -107 dBW. From the above result, it can be seen that c. 40% of channels are likely to fail against this criterion, reducing the throughput of the link by a similar amount.

In the case of a 1 km DSSS wireless bridge, for operation at the maximum 11 Mbit/s data throughput a C/I of 8 dB is required, i.e. interference should not exceed -100 dBW. The above result indicates that this will not be achievable in c.10% of locations. Where interference is higher, the link will back off to lower data rates. At 1 Mbit/s, a DSSS system can tolerate a 0 dB C/I ratio, a value which appears likely to be met at 99% of sites according to the above result.

6.2.8 RFA into RLANs

Interference from three projected densities of RFA base stations have been modelled into indoor and outdoor LANs. As noted in section 3.1.2, the current Atlantic network in Glasgow has a maximum base station density of c. 1 per km^2, however to allow for future demand growth we have also modelled base station densities of 3 and 10 per km^2.

The modelling has considered interference into indoor systems with 2 dBi gain omnidirectional antennas and outdoor RLAN systems with 10 dBi omnidirectional antennas.

6.2.8.1 Indoor victims

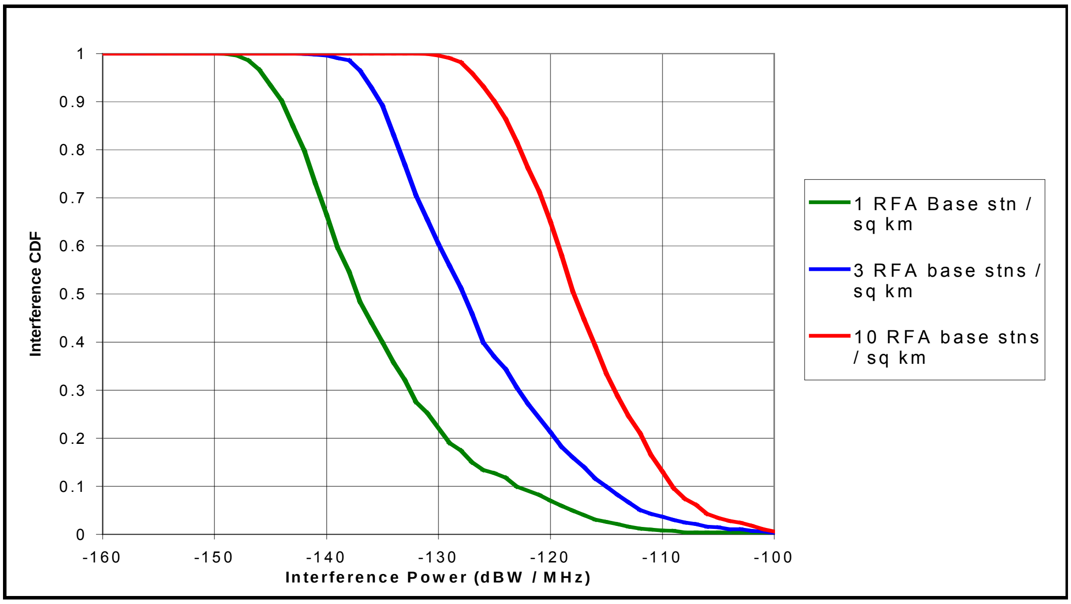

Figure 6.12 Interference CDF for RFA interferer into indoor RLAN receiver (dual slope propagation model)

The result shows that at the higher likely densities some interference into indoor RLAN systems is likely to result from RFA transmissions. The propagation model assumed here is dual slope, which is appropriate for RLANs operating on the upper floors of high rise office buildings, a likely scenario in urban business centres like Manchester or Glasgow. The effect upon RLAN systems operating at lower levels, such as in shops, where the Okumura-Hata model can be applied, is much less, as indicated below:

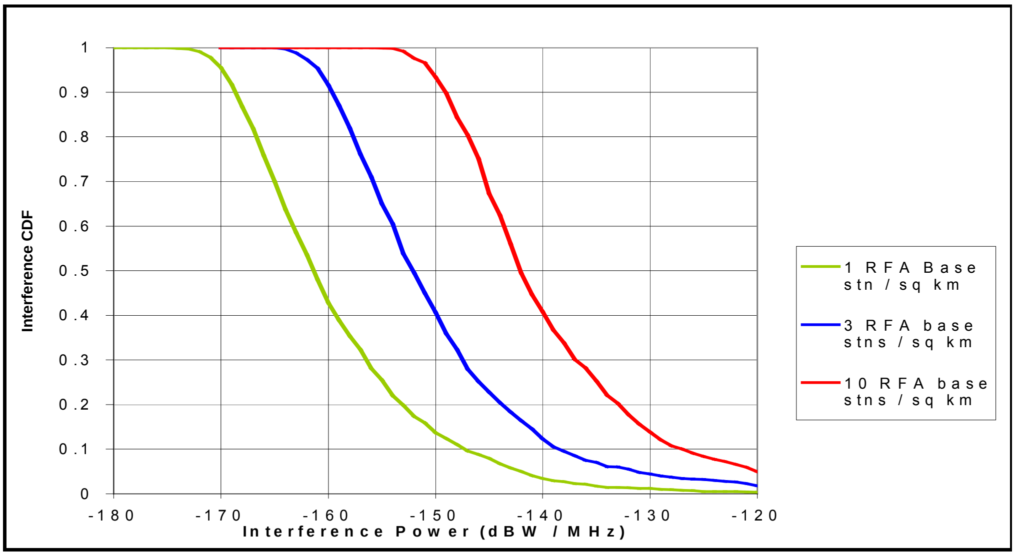

Figure 6.13 Interference CDF for RFA interferer into indoor RLAN receiver (Okumura - Hata propagation model)

6.2.8.2 Outdoor victims

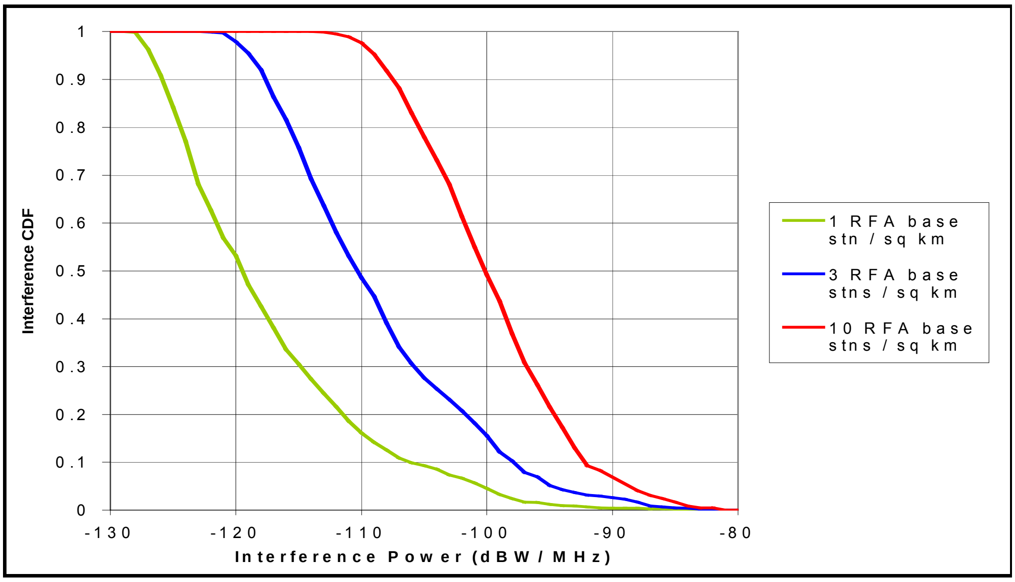

Figure 6.14 Interference CDF for RFA interferer into outdoor RLAN receiver (dual slope propagation model)

In this case, as would be expected, interference is much higher and would have the effect of limiting the working range of an outdoor system. Note however that the interference is not significantly greater than that which would be produced by other outdoor RLANs.

Throughout this study we have assumed that interference from RFA networks will be dominated by the base station emissions. This is because the base stations have greater elevation (90 metres compared with 8 metres) and higher EIRPs than the subscriber stations. The following plot confirms the validity of this assumption by comparing the cumulative interference from RFA base and subscriber stations into an outdoor RLAN receiver, assuming a fully loaded RFA network with 1 base station and 144 subscriber stations per km^2. In determining the interference from the subscriber stations, a 10 dB antenna beamwidth has been assumed. The Okumura Hata propagation model has been assumed for the subscriber stations, dual slope for the base stations (the difference reflects the much lower typical elevation of the subscriber stations).

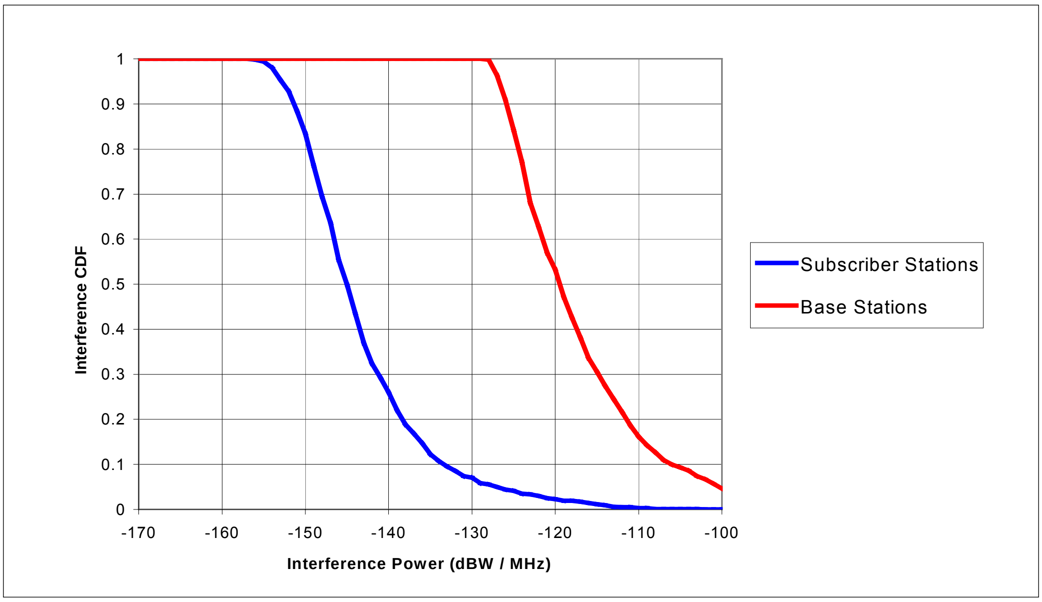

Figure 6.15 Comparison of interference from RFA base stations and subscriber stations into an outdoor RLAN receiver

6.2.9 Bluetooth into RLANs

The effect of 80 low power Bluetooth devices per km2 with an 80/20 split between indoor and outdoor systems on a typical indoor and outdoor RLAN system has been considered. We have also modelled the effect of 5 high power outdoor Bluetooth transmissions per km2 on a typical outdoor RLAN receiver. The results are shown below:

6.2.9.1 Indoor victim

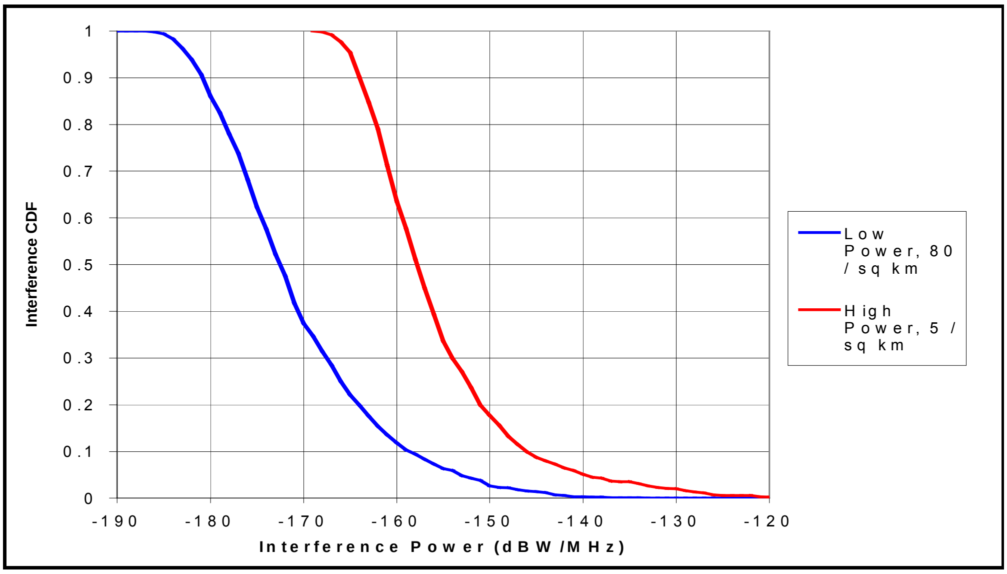

Figure 6.16 Interference CDF for Bluetooth interferers into indoor RLAN receiver

From this result it is clear that Bluetooth presents little risk of interference to indoor RLAN systems. The result also holds for intra-system interference between Bluetooth devices and suggests that this too will be negligible.

6.2.9.2 Outdoor victim

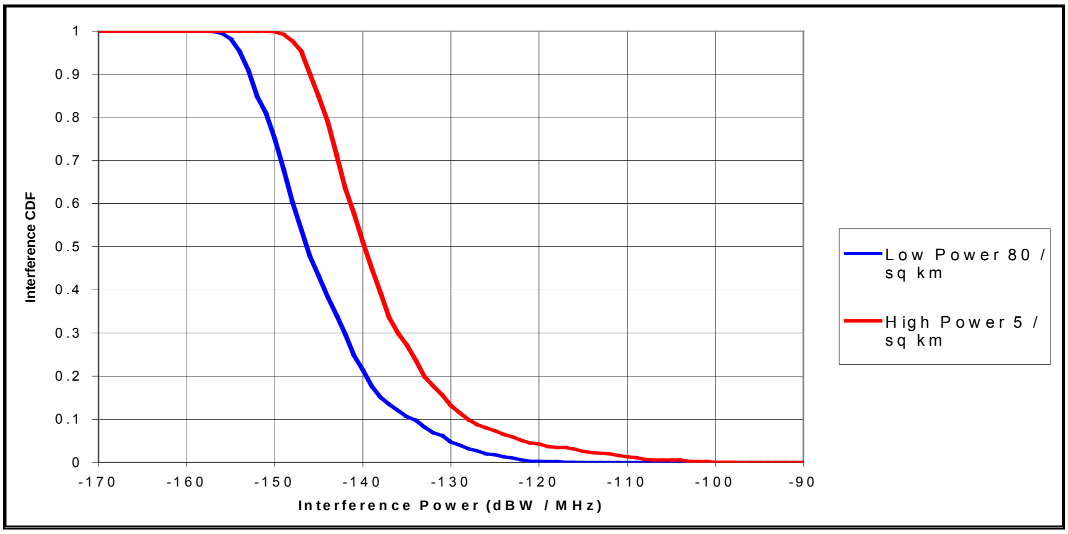

Figure 6.17 Interference CDF for Bluetooth interferers into outdoor RLAN receiver

It can be seen that the outdoor systems produce a greater level of interference but the 10% probability level remains below the RLAN receiver interference threshold. Given the self-limiting nature of outdoor RLAN systems (see section 6.2.6 above) it seems unlikely that Bluetooth will be a significant interference source even if high power (100 mW) systems are deployed in outdoor locations.

6.2.10 HomeRF into RLANs

The effect of 34 HomeRF systems/km2 with an 80/20 indoor /outdoor split has been modelled, yielding the following result:

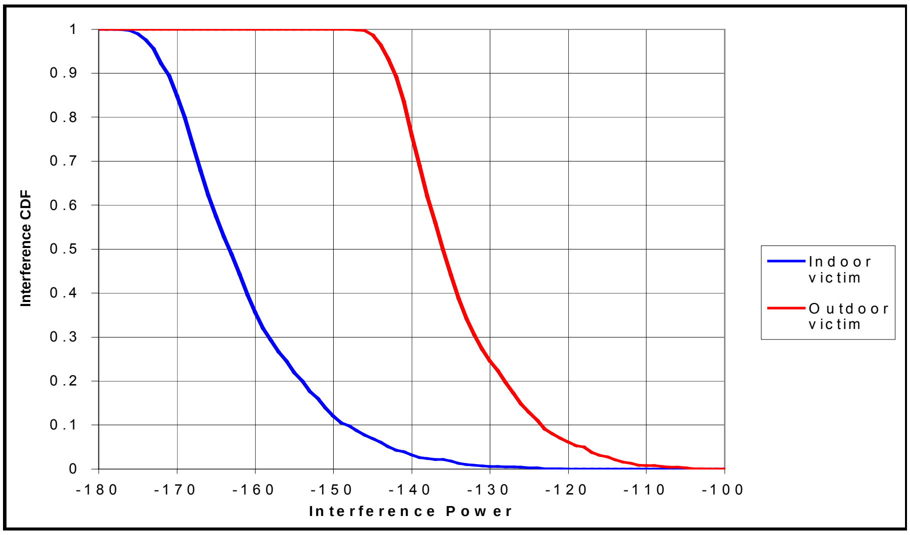

Figure 6.18 Interference CDF for HomeRF interferers into RLAN receiver

Although interference into outdoor RLAN receivers exceeds the nominal limit, in view of the self-limiting nature of the outdoor systems (i.e. their working range is liklely to be limited by the presence of other outdoor RLANs) this is unlikely to present a problem in practice.

6.2.11 Other significant interference into RLANs

The anticipated effect of OBTV and ISM interference on a typical indoor and outdoor RLAN systems is shown below.

6.2.11.1 OBTV

Interference is based on the levels derived in section 5.5.1, assuming a separation between interferer and victim of 500 metres. Taking account of the analogue OBTV spectrum mask in section 2.2.1 and assuming a line of sight path, the interference mask into an indoor RLAN receiver would be:

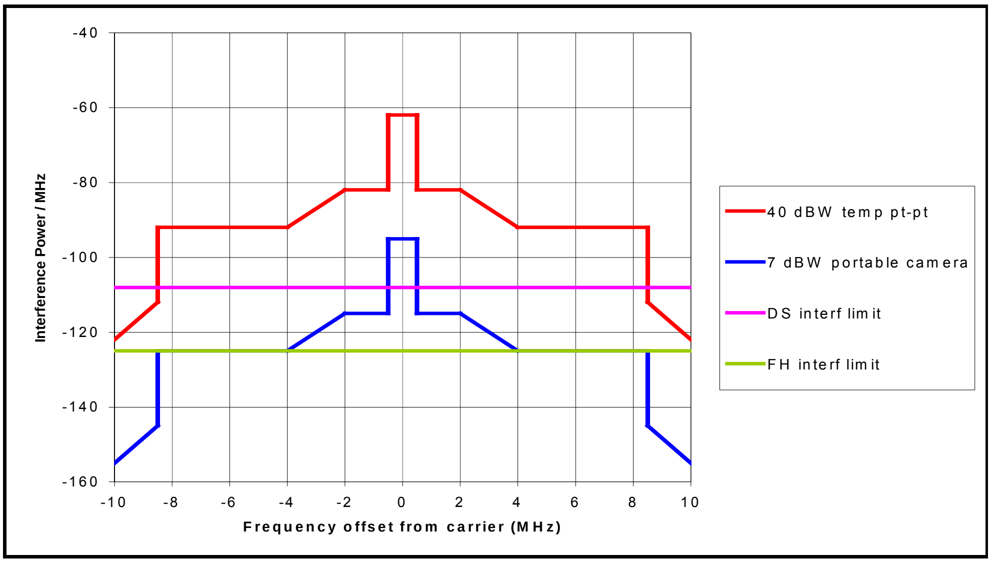

Figure 6.19 Interference from OBTV interferers into indoor RLAN receiver

It can be seen that the temporary point to point link affects FH channels over its entire 20 MHz bandwidth (i.e. at least 20 channels), while the portable camera affects an 8 MHz band. However, RLANs typically operate at receiver levels significantly above the receiver sensitivity because of the relatively high link margins, hence in practice it is unlikely that more than one or two hopping channels would be adversely affected even by an interferer at this close range. Even if all 20 channels within the interferer bandwidth were to be affected, the effect on a FHSS system would merely be to slow the data throughput by c. 25%, corresponding to the proportion of available hopping channels affected.

A DSSS system may find operation difficult if there is an OBTV broadcast underway in the vicinity with the carrier located within the victim's 22 MHz receiver bandwidth however with typical RLAN link margins problems are unlikely to arise in practice.

Outdoor RLAN systems will experience interference levels similar to those of RFA systems (see 6.2.4 above). DSSS systems in particular may become unuseable or require re-tuning if the OBTV signal lies within the wanted signal bandwidth.

6.2.11.2 ISM

For modelling purposes we have assumed that the highest levels of ISM interference encountered will be similar to those measured in Skipton by the RA, and that the emission mask will correspond to that derived from the RA's laboratory tests on a series of domestic microwave ovens (see section 2.3.1). Allowing for building penetration loss and the typical 2 dBi gain of an indoor RLAN system, the likely interference levels at the input to an indoor RLAN receiver will be:

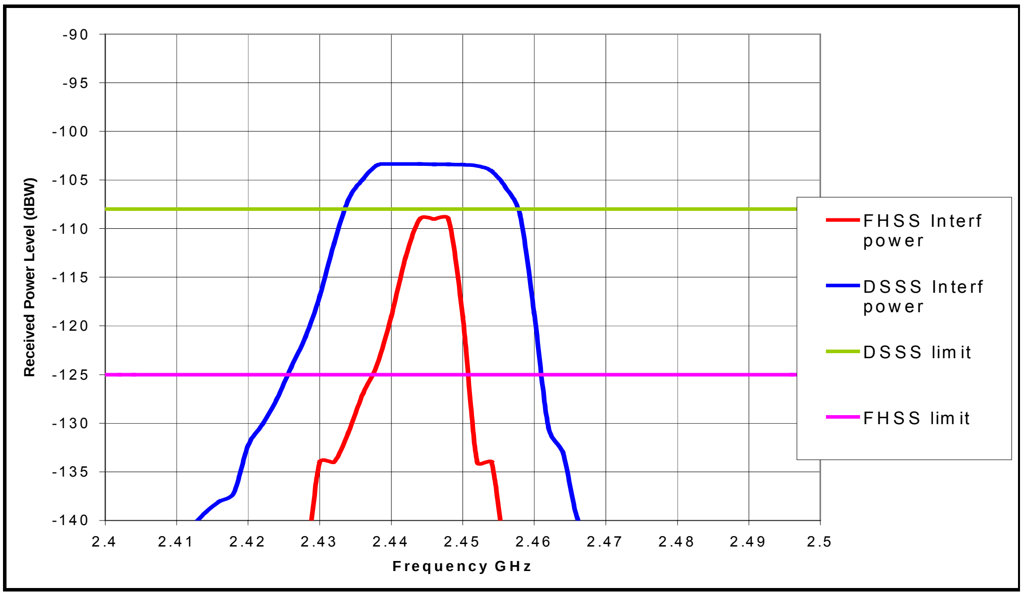

Figure 6.20 Interference from ISM equipment into indoor RLAN receiver

Here it can be seen that up to 14 of the available FH channels may suffer interference, resulting in a slowing down of data throughput of up to 18%. However a link margin if 16 dB would be sufficient to overcome ISM interference at all frequencies and as typical RLAN margins are likely to be higher than this in practice ISM interference is not considered a major issue for RLANs unless they are located close (within 2 - 3 metres) to a specific source. As the plot shows, DSSS systems require an even smaller margin and would appear most unlikely to be adversely affected by external ISM interference.

Outdoor RLAN systems are likely to suffer interference levels similar to those for RFA receivers (see 6.2.5 above).

6.2.12 Cumulative interference into RLANs

The plot below shows projected cumulative interference into a typical indoor RLAN receiver with a 2dBi gain omnidirectional antenna for the assumed high urban penetration scenario, i.e.:

- 10 RFA sources per km^2
- 800 indoor RLANs per km^2
- 1.6 outdoor RLANs per km^2
- 80 low power Bluetooth devices per km^2 (80/20 indoor / outdoor split)

- 5 outdoor high power Bluetooth devices per km^2
- 34 HomeRF systems per km^2 (80/20 indoor / outdoor split)1
- Typical urban ISM interference
- A portable analogue OBTV camera operating on a carrier frequency of 2420 MHz.

The plot also shows individual contributions from the more significant interferer types.

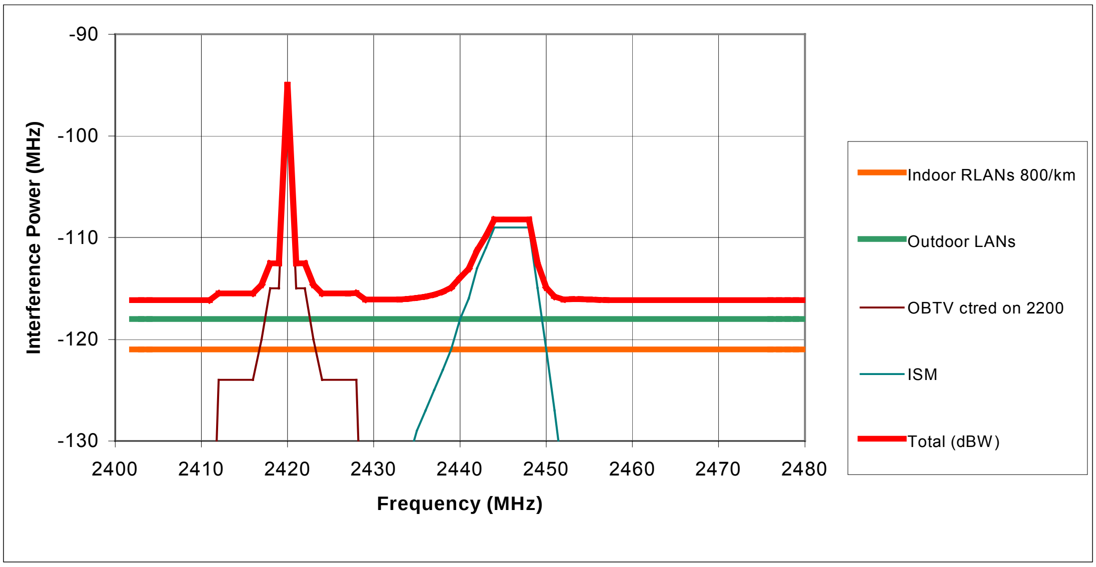

Figure 6.21 Interference contributions into indoor RLAN receiver

It can be seen that even at the highest projected RLAN densities, interference is still dominated by the effect of ISM and OBTV interference. However, the levels are such that reliable RLAN operation should be feasible providing sufficient link margins are available.

For outdoor RLAN receivers, OBTV and ISM remain dominant at specific frequencies, however the self-limiting effect of interference between outdoor systems means their effect is much less pronounced:

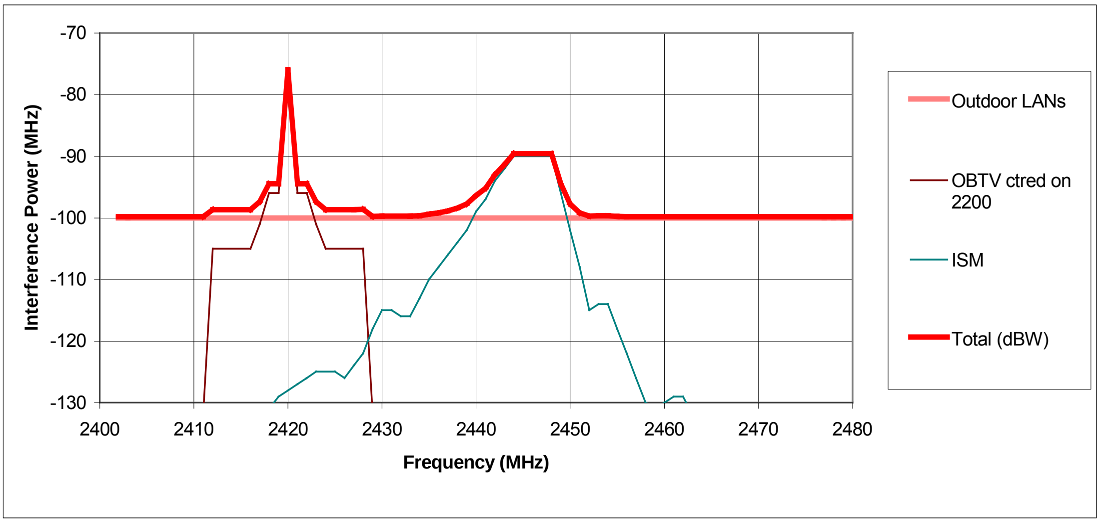

Figure 6.22 Interference contributions into outdoor RLAN receiver

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Interference in the 2.4 GHz band

This study has shown that there is already a significant amount of RF activity in the 2.4 GHz band and that there is likely to be a substantial increase in the future as increasing numbers of communication devices are deployed in the band. The types and levels of interference vary considerably both geographically and over time. Currently, the highest peak levels of interference likely to be encountered at most locations originate from ISM equipment, principally domestic microwave ovens, and OBTV transmissions. However as penetration levels increase outdoor communication systems, notably RLANs and wireless bridges, are expected to become the most significant factor in terms of interference to communication systems.

Interference from ISM equipment is highly dependent upon the time of day and location of the victim receiver. It is generally restricted to a specific part of the band and if necessary can be largely avoided by judicious choice of operating frequencies, albeit with a potential reduction in system capacity. OBTV transmissions are very sporadic and in most locations unlikely to arise more than once or twice a year, if at all. Where they do occur however, the power levels are such that disruption is almost certain to arise to any co-channel outdoor receivers in the vicinity and this should be borne in mind by those planning networks to meet specific performance criteria.

Outdoor RLANs and wireless bridges typically operate continuously and interference from these devices affects the whole of the 2.4 GHz band, making avoidance difficult or impossible. Indoor RLANs and other wireless connectivity devices present less of a problem because they are largely attenuated by building and clutter losses, however at very high densities (> 40 per km^2), even these can become significant.

It is our opinion, on the basis of this study, that the effect of Bluetooth, HomeRF and RFID devices in the 2.4 GHz band will be relatively small compared to the effect of indoor and outdoor RLAN systems. This is by virtue of the relatively low duty cycles and / or lower power levels involved. Unlike RLANs where the access points transmit continuously, emissions from these newer wireless connectivity systems are likely to be intermittent and, in the case of Bluetooth will often be at substantially lower power levels.

The following matrix summarises the anticipated worst case interference (in dBW) anticipated between various combinations of interferer and victim. The figures for interference from RLANs are based on a split of 68% / 32% in favour of frequency hopping, in line with the recent Frost and Sullivan forecast. Should DSSS achieve ascendancy, this is likely to increase potential interference levels from outdoor systems by 4 - 5 dB (indoor systems are less affected by the split because of the high densities involved - see section 6.2.1). It should be noted that an interferer producing the highest peak interference level does not necessarily have the greatest impact. As indicated above, account must be taken of the duration, geographic extent and bandwidth of the interfering signals. A continuous interference signal covering the full band and affecting large areas of a city will be more problematic than a narrow band signal occasionally deployed at a remote rural site, even if the latter is at a much higher power.

Interferer	Received interference power (dBW / MHz) RFA Base Station	Indoor RLANs	Outdoor RLANs	Bluetooth*	HomeRF*
RFA (10/km^2)	-102	-127	-93	-117	-117
Indoor RLANs (800 /km^2)	-114	-121	-113	-111	-111
Outdoor RLANs (1.6 km^2)	-110	-125	-101	-115	-115
Bluetooth (80 low pwr/ km^2 + 5 outdoor high pwr / km^2)	-131	-146	-128	-136	-136
HomeRF (34/ km^2)	-129	-149	-123	-139	-139
OBTV (portable camera 500m away)	-86	-96	-77	-86	-86
ISM (typical urban worst time of day)	-99	-109	-90	-99	-99

*Assumes outdoor operation. 10 dB should be subtracted for typical indoor scenarios.

Table 7.1 Projected probable worst case interference levels (10% probability) into 2.4 GHz communication systems

7.2 Effect of interference on system performance

The effect of interference on performance varies depending upon whether the victim uses FHSS or DSSS technology. For a FHSS system, degradation will depend on how many "lost" channels can be tolerated. In many cases there may simply be a slowing down in data throughput corresponding to the proportion of hopping channels affected. This effect would be similar to the variation in data throughput rate already experienced in other shared resource media (e.g. wired LANs or the Internet) and reductions of 10 - 20 % are likely to be acceptable for most applications. Real time services such as voice may be more problematic but discussions with suppliers and users have indicated that the temporary loss of up to 10% of channels should be tolerable.

DSSS systems can tolerate higher instantaneous levels of interference but experience a greater probability of interference occurring within the wanted signal bandwidth. The effect is particularly severe in the case of high power narrow band signals such as OBTV transmissions, which may affect only a small number of FHSS channels but may render a DSSS system inoperable if the OBTV signal lies within the wanted signal channel.

7.3 Recommendations

7.3.1 Network Planning

The practical effect of the interference levels in table 7.1 on those installing public or private networks designed to meet specific performance critieria will be to reduce the working range over which those criteria can be met. For the purposes of this study we have assumed that a typical RFA network requires a minimum C/I ratio of 15 dB and that a maximum of 10%

of FHSS channels may suffer interference above this level at any given time. The maximum working range of an RFA system designed to meet these criteria and with the technical characteristics defined in section 3.1 of this report is shown in figure 7.1 below, as a function of the cumulative interference level.

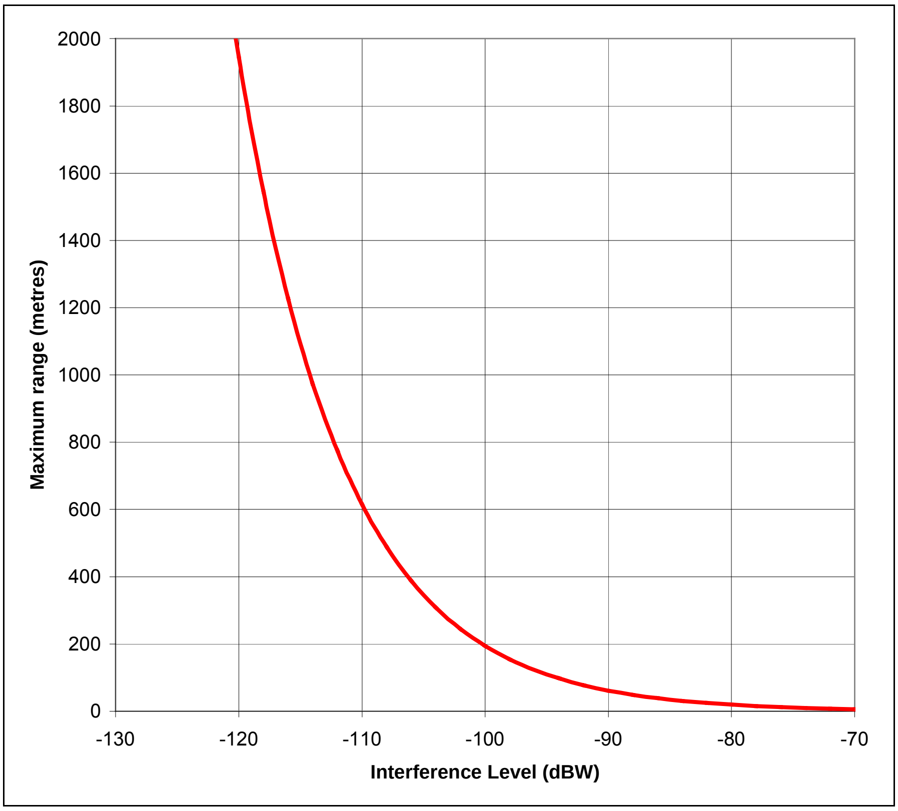

Figure 7.1 Maximum working range of a RFA base station as a function of cumulative interference level.

In the absence of external interference a typical mature RFA POTS network is likely to deploy base stations serving radii of the order of 1 - 1.25 km. Comparing the above graph with the interference levels presented in table 7.1, it is clear that the interference levels likely to be generated by OBTV, ISM equipment , outdoor LANs and other RFA networks in the same area all have the potential to reduce the maximum cell radius below 1 km, necessitating additional base stations to compensate. Indoor LANs may also have an effect although this is marginal (the projected -114 dBW level corresponds to a maximum cell radius of 1 km). The high level of projected interference between co-located high capacity RFA networks (up to -102 dBW) is likely to rule out the possibility of two unco-ordinated high capacity networks in the same geographic area maintaining a grade of service consistent with the requirements of a public telecommunications operator.

As already noted, ISM interference can be largely avoided by restricting the range of frequencies over which hopping takes place. It is difficult to plan a network to avoid OBTV interference, given its inherently unpredictable nature. However, the sporadic and narrow band nature of OBTV transmissions mean they are unlikely to be a major determinant of the long term network performance or availability, except in certain specific locations where regular transmissions take place. Outdoor RLANs on the other hand may be deployed substantially anywhere and typically (in the case of FHSS systems) operate over the full 2.4 GHz band. It is thus likely that at some future point it would be necessary for an RFA nework to adopt smaller cell sizes (and hence deploy more base stations) than it would otherwise in areas where outdoor RLAN systems are present. In the light of these results it is recommended that those planning networks at 2.4 GHz should take account of the likely increase in interference levels as interferer system penetrations rise, and build sufficient flexibility into their networks to deliver the increased link margins which may become necessary as a result.

The results indicate that operation of high performance telecommunication networks in the City of London, which in addition to having an exceptionally high density of potential RLAN users is also subject to a relatively high number of OBTV transmission, is unlikely to be viable. Operation in other, more typical urban areas should be feasible providing sufficient flexibility exists to increase link margins to counter projected future interference levels. It is assumed that any RFA network will deploy sectored, downtilted antennas to minimise the effect of interference from outside the intended coverage area.

Although similar effects will be seen with RLAN and other communication systems at high interferer densities, the effect is less serious because these systems typically operate with higher link margins to start with. The use of 2.4 GHz RLAN technology to deliver reliable wide area outdoor communication is likely to be compromised at higher link densities, principally due to the effect of other outdoor systems including RLANs and RFA transmitters. This will be particularly so for systems employing highly elevated omnidirectional antennas. Consequently we expect such outdoor use to be self limiting in terms of the density of transmitters which may be accommodated in a given area whilst continuing to deliver acceptable performance. For example, figure 6.9 shows that the intra - system interference level between outdoor RLANs at a density of 1.6 per km^2 is -100 dBW. To maintain a 15 dB C/I ratio, a received signal level of -85 dBW would thus be required. For an outdoor RLAN operating at the current -10 dBW EIRP limit and with an omnidirectional 10 dBi gain receive antenna, this will limit the reliable working range to c. 200 metres, which is unlikely to be sufficient for many current outdoor applications such as those referenced in section 3.2.8.

7.3.2 FHSS vs DSSS

On the basis of currently available technology and recent standards developments, it is likely that FHSS systems will provide greater resilience to interference and will therefore be preferable for applications such as RFA where it is necessary to deliver a specific grade of service. Whilst future developments such as the introduction of DSSS systems with higher chip rates which would enable operation of true CDMA can not be ruled out, even these are likely to be unsuitable for operation in the presence of very high power interference sources such as OBTV. We would therefore advise against the deployment of DSSS for RFA purposes in areas where interference is likely to arise

DSSS is likely to provide greater throughput per system for the foreseeable future, by virtue of the wider RF channels, however this benefit may be compromised to some extent where multiple DSSS systems are co-located. This may for example lead to problems if more than three outdoor DSSS systems are operated in the same geographic region, where the transmission path between interferer and victim may be substantially line of sight.

7.3.3 RLAN EIRP limits

The introduction of a 500 mW EIRP limit for RLANs, as recently proposed to ERC Project Team SE24, would if widely adopted lead to a 7 dB increase in the interference levels cited for RLAN interferers in table 7.1. Such an increase would in the case of outdoor systems have a significant effect upon the viability of RFA systems unless these systems were also permitted to adopt the higher power level. Since the current 100 mW limit is generally accepted as sufficient to provide effective indoor coverage at ranges up to 100 metres, there appears to be little merit in the proposal to increase the power, other than to make unlicensed RLANs more attractive for long range outdoor applications. Such applications have been identified as potentially the most serious interference source in the longer term and it is therefore our view that such a move should be resisted. At the very least, we would suggest that any higher limit, which may be introduced, should be restricted to indoor use and for applications involving limited duty cycles, as is currently proposed for high power RFID devices.

7.3.4 Recommendations for future work

It is recognised that the market for 2.4 GHz communications systems is still relatively immature and that there may be further development in the regulatory or standards for a which affect the assumptions used in this analysis. The proposal to increase the maximum EIRP for RLAN devices is cited above as an example. There is also the possibility that alternative forms of DSSS technology may be adopted in the future, enabling greater scope for co-location than is feasible with current systems.

It is also unclear at this stage how diverse a range of applications may arise for the emerging HomeRF and Bluetooth technologies. We have assumed a very high penetration of these technologies and allowed for a substantial element of outdoor use, which should provide something approaching a realistic worst case scenario. However, it is recommended that the a further evaluation of the various interference scenarios in the band should be carried out in 1 - 2 years, when the direction of market development for these devices has become more clear.

8 GLOSSARY

ADPCM	Adaptive Differential Pulse Code Modulation
AP	RLAN Access Point
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CCA	Clear Channel Assessment
CCK	Cyclic Code Keying
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CEPT	Conference of European Post and Telecommunications Administrations
C/I	Carrier to Interference Ratio
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
CW	Continuous Wave
DSSS	Direct Sequence Spread Spectrum
DSP	Digital Signal Processing
EIRP	Effective Isotropically Radiated Power
EPOS	Electronic Point of Sale
ERC	European Radiocommunications Committee
ETSI	European Telecommunications Standards Institute
EU	European Union
FDMA	Frequency Division Multiple Access
FHSS	Frequency Hopping Spread Spectrum
FM	Frequency Modulation
FSPL	Free Space Path Loss
FSK	Frequency Shift Keying
GAP	DECT Generic Access Protocol
IEEE	Institution of Electrical and Electronic Engineers
I-ETS	Interim European Telecommunications Standard
IF	Intermediate Frequency
ISDN	Integrated Services Digital Network

ISM	Industrial, Scientific and Medical
JFMG	Joint Frequency Management Group
MAC	Multiple Access Control
OBTV	Outside Broadcast Television
OFDM	Orthogonal Frequency Division Multiplex
PCMCIA	Personal Computer Memory Card International Association
POTS	Plain Old Telephony Service
PSK	Phase Shift Keying
PSTN	Public Switched Telecommunications Network
QPSK	Quaternary Phase Shift Keying
RA	UK Radiocommunications Agency
RF	Radio Frequency
RFA	Radio Fixed Access
RFID	RF Identification
RLAN	Radio Local Area Network
RSSI	Received Signal Strength Indicator
S/N	Signal to Noise Ratio
SRD	Short Range Device
SWAP	Shared Wireless Application Protocol
TDMA	Time Division Multiple Access
WER	Word Error Rate